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ORBITAL OPERATIONS STUDY

VOLUME II - INTERFACING ACTIVITIES ANALYSES

PART I - INTRODUCTION AND SUMMARY

FINAL REPORT

MAY 1972

APPROVED BY

L. R. Hogan

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Study Manager
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TECHNICAL REPORT INDEX/ABSTRACT

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DESCRIPTIVE TERMS

** Alternative Design/Operational Approaches
** Design Concept Models
** Functional Requirements
** Preferred Approach Selection
** Design/Operational Influences

ABSTRACT

This volume represents an extraction and condensation of the pertinent analyses data from fourteen interfacing activities. The significant analyses results have been grouped into four categories as follows:

STRUCTURAL & MECHANICAL ACTIVITY GROUP

- o Mating
- o Orbital Assembly
- o Separation
- o EOS Payload Deployment
- o EOS Payload Retraction & Stowage

DATA MANAGEMENT ACTIVITY GROUP

- o Communications
- o Rendezvous
- o Stationkeeping
- o Detached Element Operations

SUPPORT OPERATIONS ACTIVITY GROUP

- o Crew Transfer
- o Cargo Transfer
- o Propellant Transfer
- o Attached Element Operations
- o Attached Element Transport

FOREWORD

This report contains the results of the analyses conducted by the Space Division of North American Rockwell during the Orbital Operations Study, Contract NAS9-12068, and is submitted in accordance with line item 7 of the Data Requirements List (DRL 7).

The data are presented in three volumes and three appendixes for ease of presentation, handling, and readability. The report format is primarily study product oriented. This study product format was selected to provide maximum accessibility of the study results to the potential users. Several of the designated study tasks resulted in analysis data across elements and interfacing activities (summary level); and also analysis data for one specific element and/or interfacing activity (detailed level). Therefore, the final report was structured to present the study task analysis results at a consistent level of detail within each separate volume.

The accompanying figure illustrates the product buildup of the study and the report breakdown. The documents that comprise the reports are described below:

Volume I - MISSION ANALYSES, contains the following data:

- o Generic mission models that identify the potential earth orbit mission events of all the elements considered in the study
- o Potential element pair interactions during on-orbit operations
- o Categorized element pair interactions into unique interfacing activities

Volume II - INTERFACING ACTIVITIES ANALYSIS, contains the following data:

- o Cross reference to the mission models presented in Volume I
- o Alternate approaches for the interfacing activities
- o Design concept models that are adequate to implement the approaches
- o Operational procedures to accomplish the approaches
- o Functional requirements to accomplish the approaches
- o Design influences and preferred approach selection by element pairs.

This volume is subdivided into four books or parts which are:

Part 1. INTRODUCTION AND SUMMARY - Condensed presentation of the significant results of the analyses for all interfacing activities

Part 2. STRUCTURAL AND MECHANICAL ACTIVITY GROUP

- o Mating
- o Orbital Assembly
- o Separation
- o EOS Payload Deployment
- o EOS Payload Retraction and Stowage

Part 3. DATA MANAGEMENT ACTIVITY GROUP

- o Communications
- o Rendezvous
- o Stationkeeping
- o Detached Element Operations

Part 4. SUPPORT OPERATIONS ACTIVITY GROUP

- o Crew Transfer
- o Cargo Transfer
- o Propellant Transfer
- o Attached Element Operations
- o Attached Element Transport

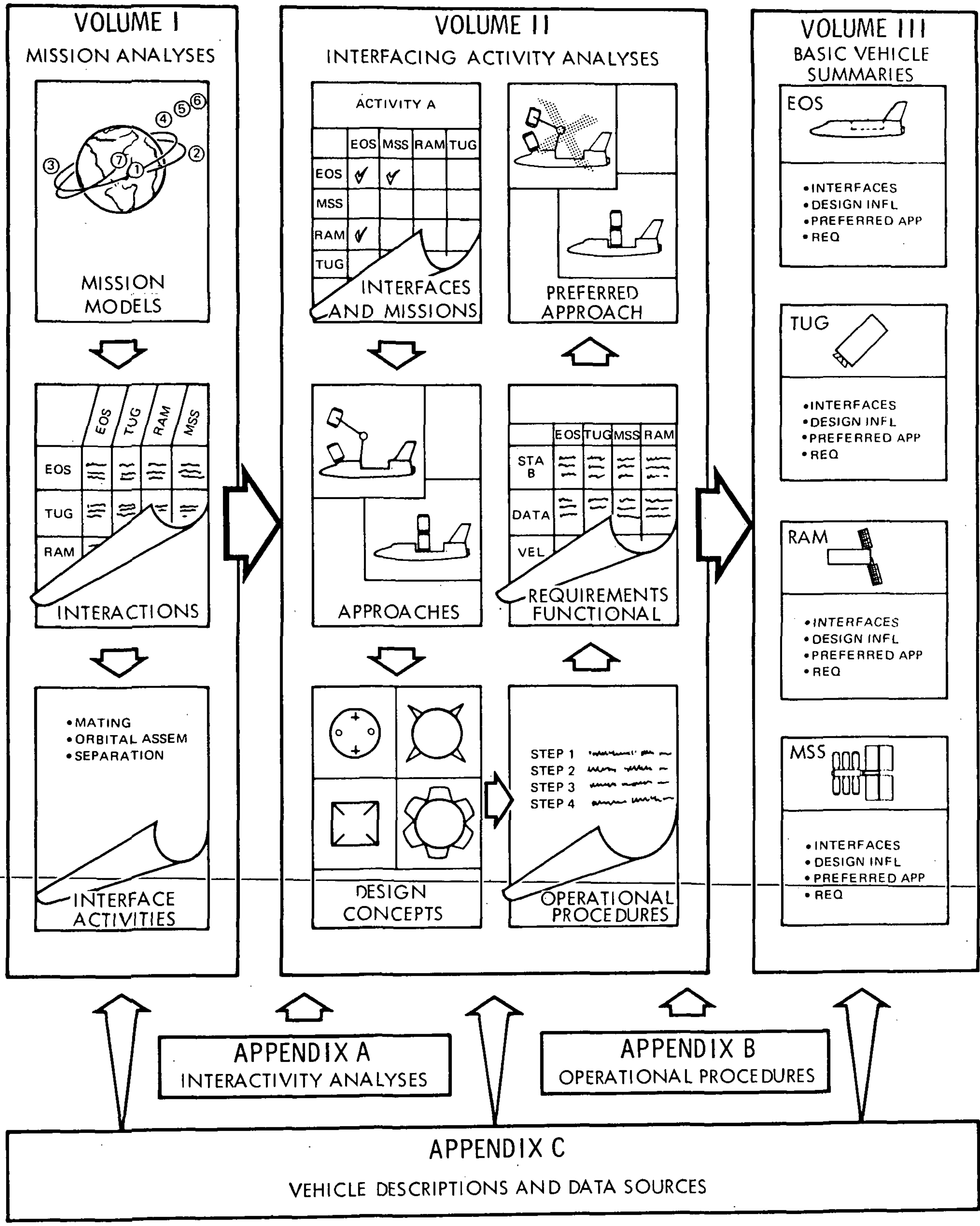
Volume III - BASIC VEHICLE SUMMARIES, contains a condensed summary of the study data pertaining to the following elements:

- o Earth Orbital Shuttle
- o Space Tug
- o Research and Applications Modules
- o Modular Space Station

Appendix A - INTERACTIVITY ANALYSES, contains many of the major trades and analyses conducted in support of the conclusions and recommendations of the study.

Appendix B - OPERATIONAL PROCEDURES, contains the detailed step-by-step sequence of events of each procedure developed during the analysis of an interfacing activity.

Appendix C - VEHICLE DESCRIPTIONS AND DATA SOURCES, presents a synopsis of the characteristics of the program elements that were included in the study (primarily an extraction of the data in Appendix I of the contract statement of work), and a bibliography of the published documentation used as reference material during the course of this study.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MISSION ANALYSES
MISSION MODELS
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SECTION 1. INTRODUCTION

The technical approach followed during the conduct of this orbital operations study was designed to cope with the ever present problem of breadth versus depth. Initially, a broad spectrum of data was accumulated encompassing all the interfacing of the program elements identified in the study plan. The application of appropriate evaluation and selection criteria progressively narrowed the scope and increased the depth of the analysis. Figure 1-1 illustrates this top level analysis flow.

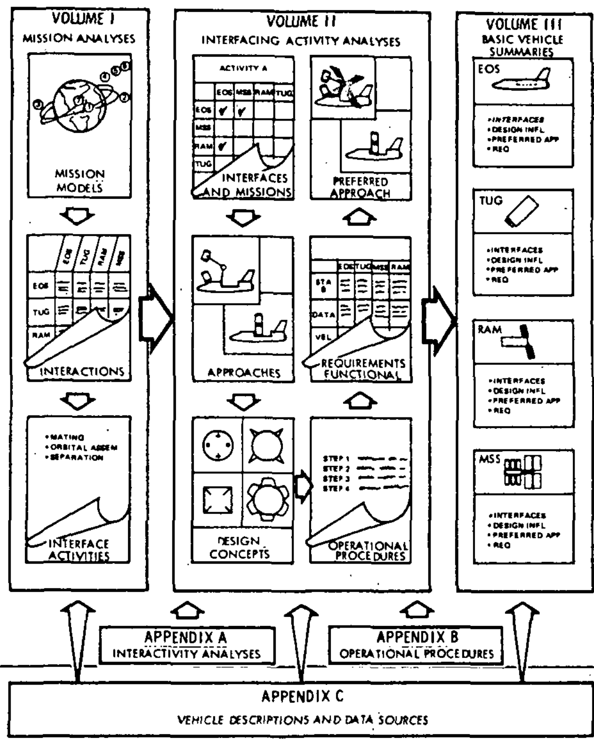


Figure 1-1. Orbital Operations Top Level Flow

The mission analyses concentrated on the broad scope of potential interactions that can occur in earth orbit between any of the elements in the study inventory. Some 40 missions generated by individual element studies were evaluated to synthesize generic mission models that would encompass the potential element pair interactions. The key functions and operational/design approaches were extracted from these mission models.

Fourteen separate interfacing activities were selected for in-depth analyses. Each activity was investigated for (1) interfaces, (2) alternate approaches, (3) operational procedures, (4) functional requirements, and (5) design influences. The nalysis results are summarized in this document (Volume II, Part 1) and detailed in Volume II, Parts 2, 3 and 4.

MISSION MODELS AND INTERFACING ELEMENTS

One of the primary purposes of mission models was to identify all element-to-element interfaces that can occur involving any reasonable combination of elements in the study inventory. A second and equally important purpose was to identify all interfacing activities that can occur between interfacing elements in earth orbit and to relate these to each element-to-element interface

Based upon an analysis of previous individual element studies approximately 40 design reference missions were identified. Regrouping and collating the potential uses of the various elements permitted the reduction of mission models to a generic set of eleven. The 11 mission models are listed on Figure 1-2 and are grouped into five categories according to the primary propulsive vehicle involved.

As the mission model titles indicate, similar mission objectives are accomplished by different mission models. The term "emplacement" is used to signify the delivery of a payload to space as opposed to delivery of a payload to another element. The term "retrieval" signifies the picking-up of a payload from space and not from another element. Therefore, "retrieval" is the reverse of "emplacement." The term "logistics" is used to signify the delivery of a payload to another element, picking-up of a payload from another element, or a combination of the two. The term "sortie" applies to a mission in which an experiment's payload remains attached to the supporting vehicle. The term "staged" and "non-staged" refer to two-stage and single-stage propulsive vehicles, respectively. The term "disposal" refers to the removal of expended elements from earth orbit.

VEHICLE	MISSION MODELS		INTERFACING ELEMENTS
EARTH ORBITAL SHUTTLE	MM-1	EMPLACEMENT	RAM; SATELLITE; KICKSTAGE; TUG; FIRST MOD OF MSS, OLS, OPD, CLS
	MM-2	LOGISTICS/RETRIEVAL	MSS; CLS; OLS; RAM; TUG; SATELLITE; EOS; OPD; CARGO, PROPELLANT, LSB MODS
	MM-3	SORTIE	RAM
SPACE BASED TUG	MM-4	RETRIEVAL/EMPLACEMENT	RAM; SATELLITE; CLS; TUG; OPD; EOS; MSS; OLS; OIS
	MM-5	LOGISTICS	LLT; RAM; SAT; MSS; CLS; TUG; EOS; OPD; CARGO MODS
	MM-6	DISPOSAL	CLS; OIS; OPD; MSS; OPD
GROUND BASED TUG	MM-7	EMPLACEMENT/SORTIE	TUG; SAT; RAM
	MM-8	LOGISTICS/RETRIEVAL	TUG; CLS; SAT; MSS; RAM; OPD; EOS; PROPEL, CARGO MODS
OIS	MM-9	DELIVERY	CLS; OLS; OPD; TUG
CISLUNAR SHUTTLE	MM-10	STAGED LOGISTICS	OPD; EOS; TUG; OIS; RAM; OLS; LSB; MSS; SAT; PROPEL, CARGO MODS
	MM-11	NONSTAGED LOGISTICS	OPD; EOS; TUG; OIS; RAM; OLS; LSB; MSS; SAT; PROPEL, CARGO MODS

Figure 1-2. Mission Models and Interfacing Elements

TECHNICAL ANALYSES DOCUMENTATION

Fourteen Key Functions from the Mission Analyses (Volume I) were identified for detailed analyses. The results of the analyses have been structured into a series of separate reports to facilitate their use. Figure 1-3 displays the various reports and identifies the major topics.

Each of the key functions of Volume I were titled Interfacing Activities with the analyses results grouped into three reports (Vol. II Part 2, Part 3, and Part 4. Therefore the individual activities are separate sections of the respective reports and identically structured.

The two appendicies contain detail technical data of which the pertinent results have been summarized in the appropriate sections of the Volume II books.

This summary report represents an extraction and a condensation of the significant results from each activity and the two appendicies.

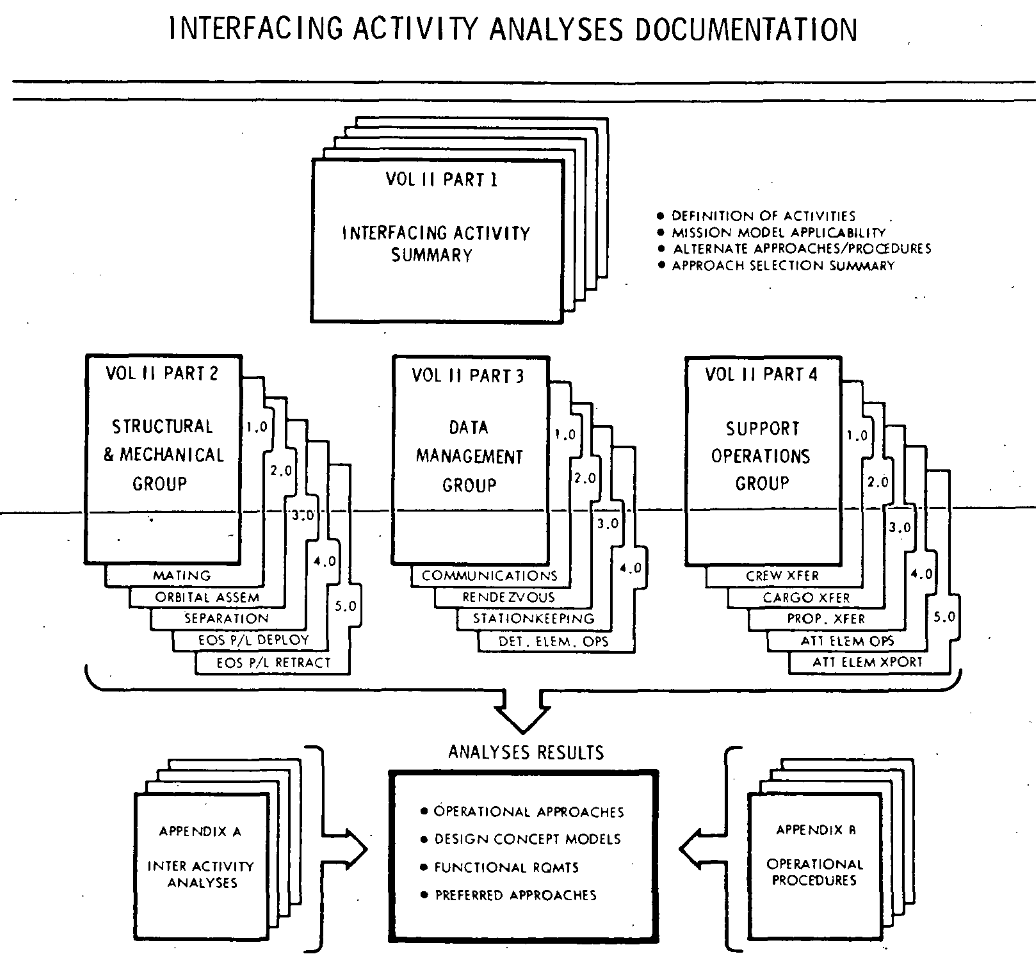


Figure 1-3. Technical Analyses Documentation

INTERFACING ACTIVITY DEFINITION

Based upon the extensive mission model activity conducted in this study, a total of 14 interfacing activities have been identified. The 14 activities listed and defined in Figure 1-4 include every type of interaction pertinent to this study that can occur between space elements in earth orbit. An attempt was made to derive a list of mutually exclusive activities; however, some overlap was inevitable in order to provide the most usable packaging of data.

Volume II, Part 2	
MATING The attachment in earth orbit of any two elements (or modules), including the operations of final closure prior to contact ORBITAL ASSEMBLY The joining together of two or more major parts to form a particular configuration of a single operational element in earth orbit, or to facilitate transport to lunar orbit or high-energy earth orbit SEPARATION The physical uncoupling of two mated elements and the subsequent maneuvers required to provide adequate clearance between elements	EOS PAYLOAD DEPLOYMENT The removal of a payload from the orbiter cargo bay and readying it for operation or separation EOS PAYLOAD RETRACTION The insertion of a payload into the orbiter cargo bay subsequent to initial mating of the payload to the orbiter
Volume II, Part 3	
COMMUNICATIONS The transmission of sound, video, and digital/analog data via space links from element-to-element and from element-to-ground RENDEZVOUS The operations required to achieve close proximity of one element to another for purposes of stationkeeping and/or mating	STATIONKEEPING The maintaining of a predetermined (not necessarily fixed) relative position between two orbiting elements DETACHED ELEMENT OPERATIONS The operational support required by a free-flying element from another element and/or ground control
Volume II, Part 4	
CREW TRANSFER The transfer of personnel between two elements in orbit CARGO TRANSFER The transfer of solid and fluid cargo between two elements in orbit PROPELLANT TRANSFER The transfer of large quantities of liquid hydrogen and liquid oxygen between elements in orbit	ATTACHED ELEMENT OPERATIONS Support by one element to another attached element while the latter is operating or being serviced, checked out, or stored ATTACHED ELEMENT TRANSPORT Support by a major propulsive element to an attached payload (element or module) during transport from one orbit to another

Figure 1-4. Interfacing Activity Definition

INTERFACING ACTIVITIES AND MISSION MODEL APPLICABILITY

To provide supplemental visibility at the mission model level, Figure 1-5 identifies all of the interfacing activities that can occur in each of the 11 generic mission models. Note that all 14 interfacing activities occur in mission models MM-2, MM-5, MM-8, MM-10, and MM-11. Each of these mission models encompasses a logistic mission application.

This cross index provides traceability between the technical data from an individual activity documented in Volume II to the corresponding mission model analyses documented in Volume I.

	INTERFACING ACTIVITIES → / MISSION MODELS ↓	VOLUME II, PART 2					VOLUME II, PART 3				VOLUME II, PART 4				
		MATING	ORBITAL ASSEMBLY	SEPARATION	EOS PAYLOAD DEPLOYMENT	EOS PAYLOAD RETRACTION	COMMUNI-CATIONS	RENDEZVOUS	STATION KEEPING	DETACHED ELEMENT OPERATIONS	CREW TRANSFER	CARGO TRANSFER	PROPELLANT TRANSFER	ATTACHED ELEMENT OPERATIONS	DETACHED ELEMENT TRANSPORT
EOS	MM-1 EMPLACEMENT	NA	NA	√	√	√	√	NA	√	√	NA	NA	NA	NA	√
EOS	MM-2 LOGISTICS/ RETRIEVAL	√	√	√	√	√	√	√	√	√	√	√	√	√	√
EOS	MM-3 SORTIE	NA	NA	NA	√	√	√	NA	NA	NA	√	√	√	√	√
SPACE TUG	MM-4 RETRIEVAL/ EMPLACEMENT	√	NA	√	√	√	√	√	√	√	√	√	√	√	√
SPACE TUG	MM-5 LOGISTICS	√	√	√	√	√	√	√	√	√	√	√	√	√	√
SPACE TUG	MM-6 DISPOSAL	√	NA	√	NA	NA	√	√	NA	√	√	√	√	√	√
GND TUG	MM-7 EMPLACEMENT/ SORTIE	√	NA	√	√	√	√	√	√	√	NA	NA	NA	√	√
GND TUG	MM-8 LOGISTICS/ RETRIEVAL	√	√	√	√	√	√	√	√	√	√	√	√	√	√
OIS	MM-9 DELIVERY	√	√	√	NA	NA	√	√	NA	NA	NA	NA	NA	NA	√
CLS	MM-10 STAGED LOGISTICS	√	√	√	√	√	√	√	√	√	√	√	√	√	√
CLS	MM-11 NONSTAGED LOGISTICS	√	√	√	√	√	√	√	√	√	√	√	√	√	√

Figure 1-5. Interfacing Activities and Mission Model Applicability

TECHNICAL DATA OUTLINE

The analyses results from each of the 14 interfacing activities are formated to an identical outline as illustrated by Figure 1-6. Each of the major headings are separate subsections.

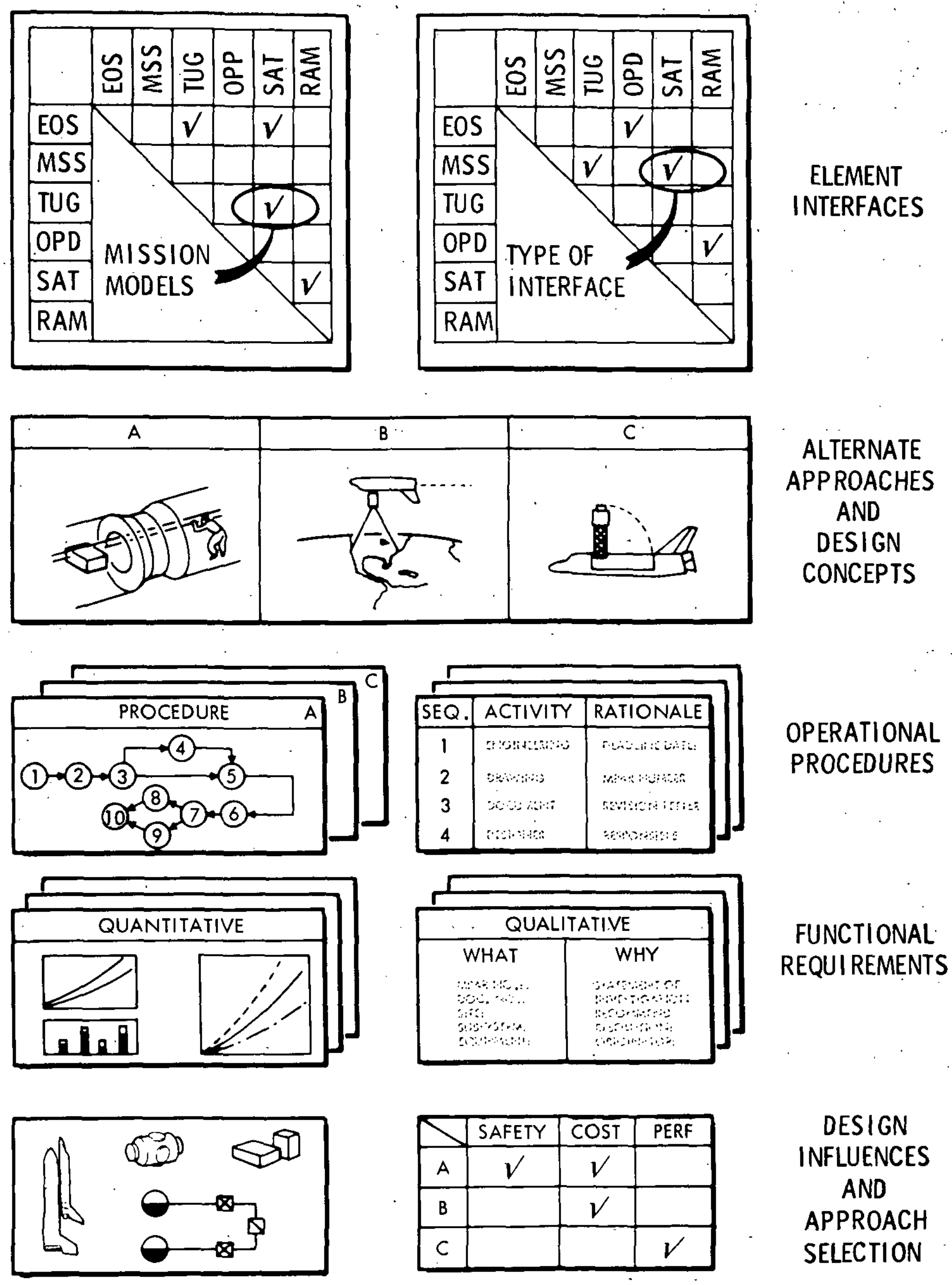


Figure 1-6. Technical Data Outline

ELEMENT INTERFACES

A separate interfacing matrix was developed for each interfacing activity to insure all vehicle pairs were considered in the analyses. A second matrix was also prepared to provide traceability between each activity and the mission models of Volume I. Figure 1-7 is an example of the matrix formats utilized.

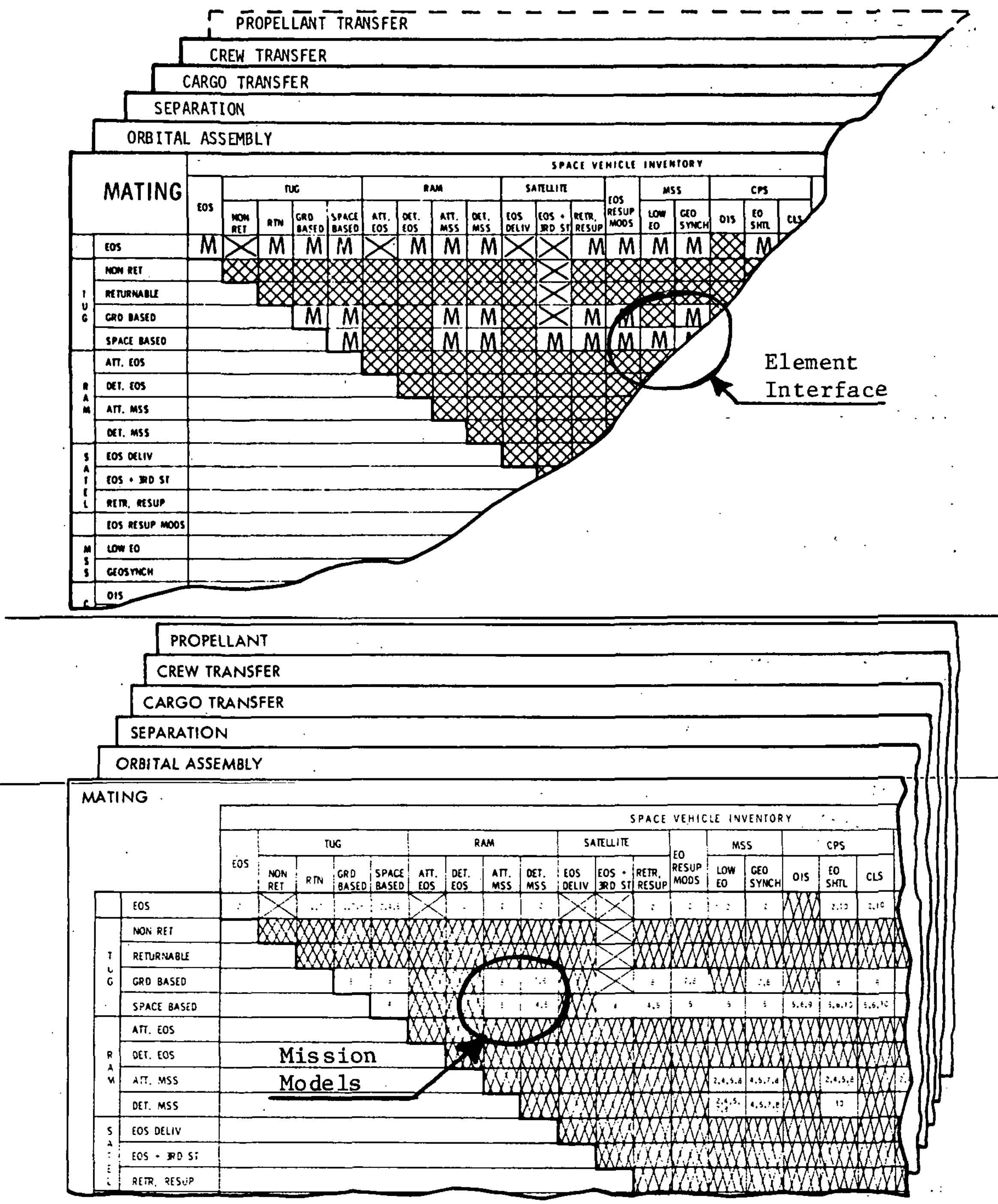


Figure 1-7. Element Interfaces

ALTERNATE APPROACHES

The key functions (activities) and approaches that were selected for further analysis are summarized in Figures 1-8, 1-9, and 1-10. The fourteen activities have been structured into three groups of related approaches: (1) Structural and Mechanical, (2) Data Management, and (3) Support Operations. The alternate approaches that are illustrated in the three figures represent a reduction from the full complement of originally identified.

Structural and Mechanical Activity Group Approaches

The approaches illustrated by Figure 1-8 are summarized in Section 2.0 of this document and detailed in Volume II, Part 2.

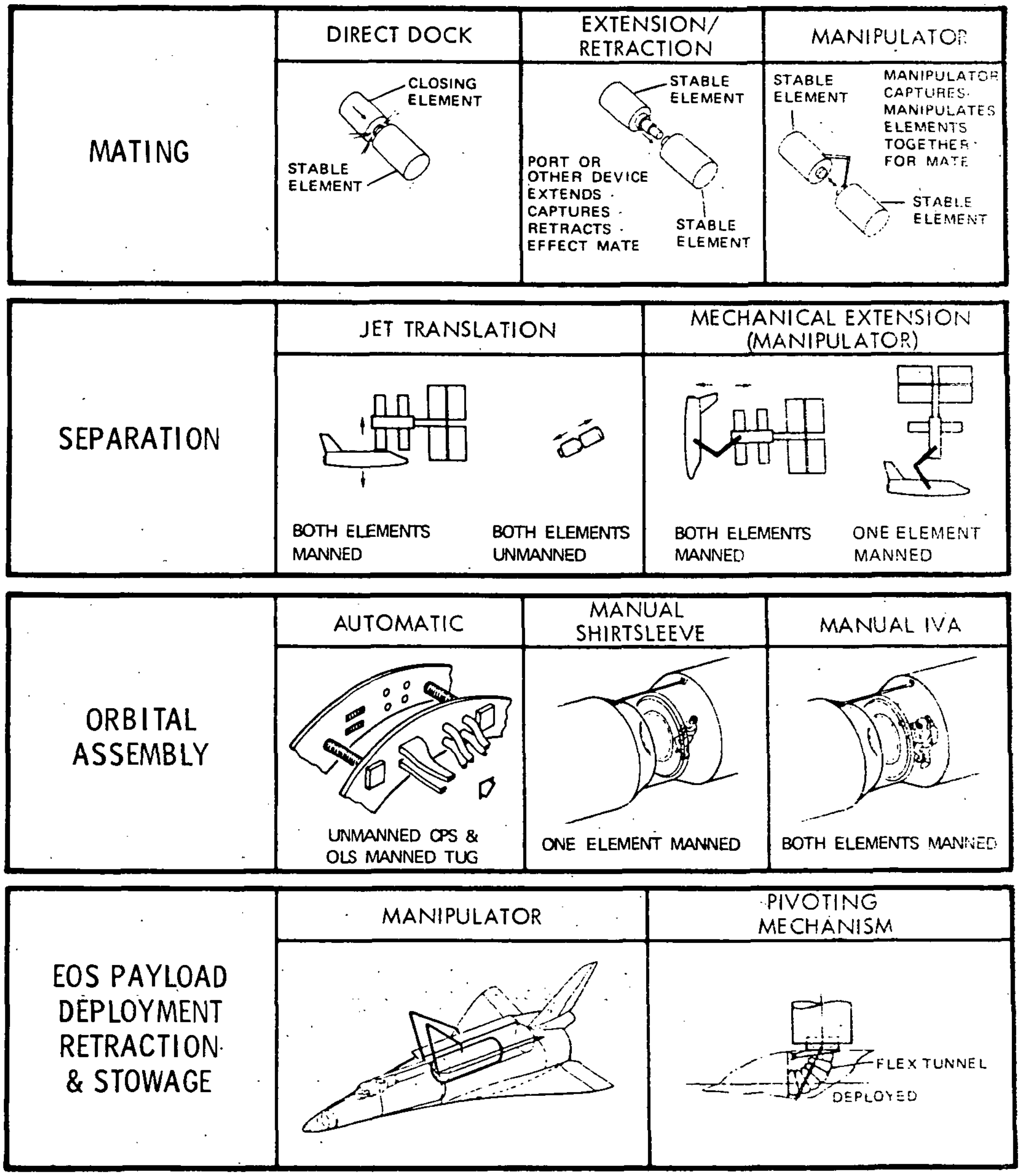


Figure 1-8. Structural & Mechanical Activity Group Approaches

Data Management Activity Group Approaches

The approaches illustrated by Figure 1-9 are those selected for in-depth analysis for which the results are summarized in Section 3.0 of this document and detailed in Volume II, Part 3.

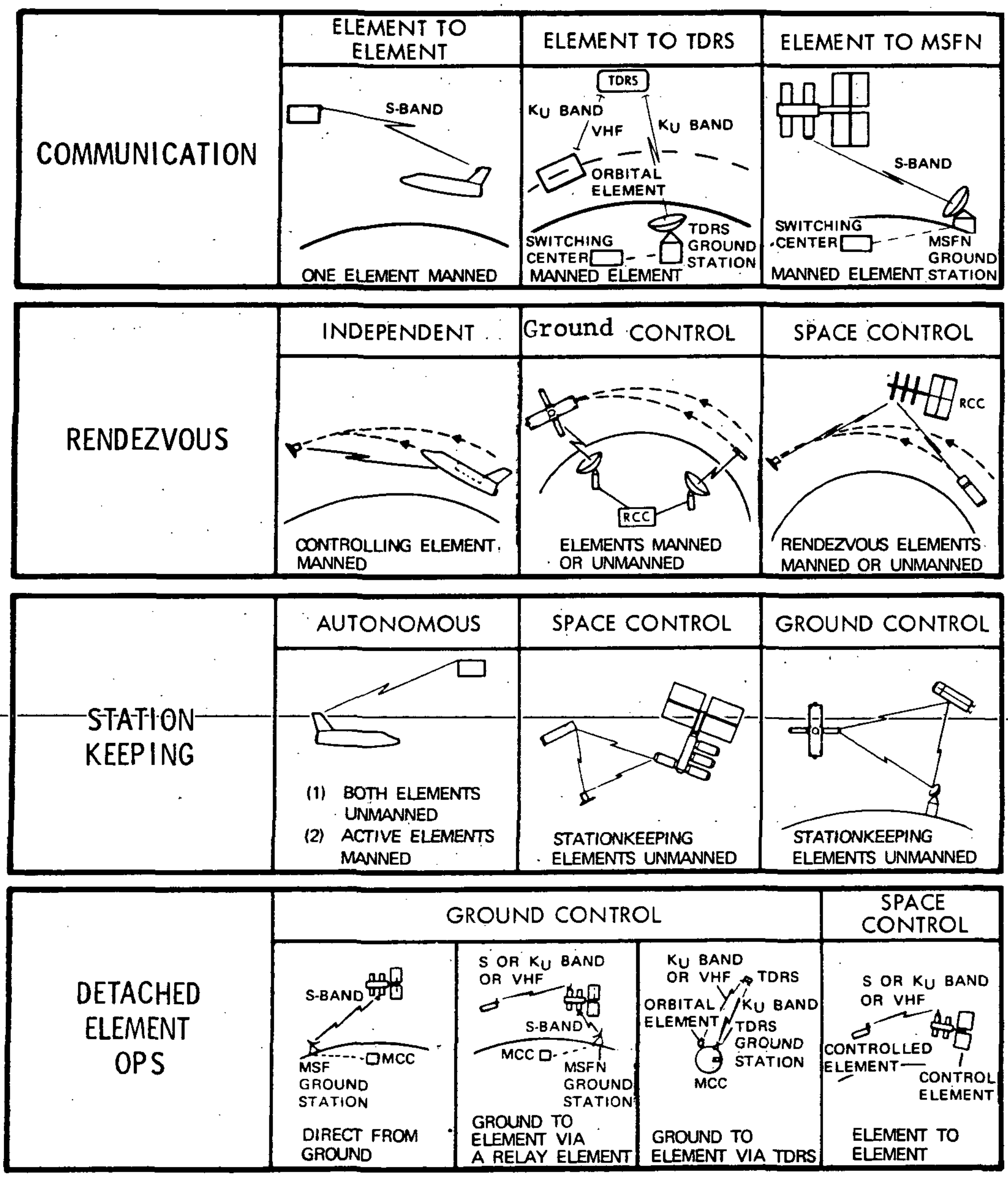


Figure 1-9. Data Management Activity Group Approaches

Support Operations Activity Group Approaches

The approaches illustrated by Figure 1-10 are those selected for in-depth analysis for which the results are summarized in Section 4.0 of this document and detailed in Volume II, Part 4.

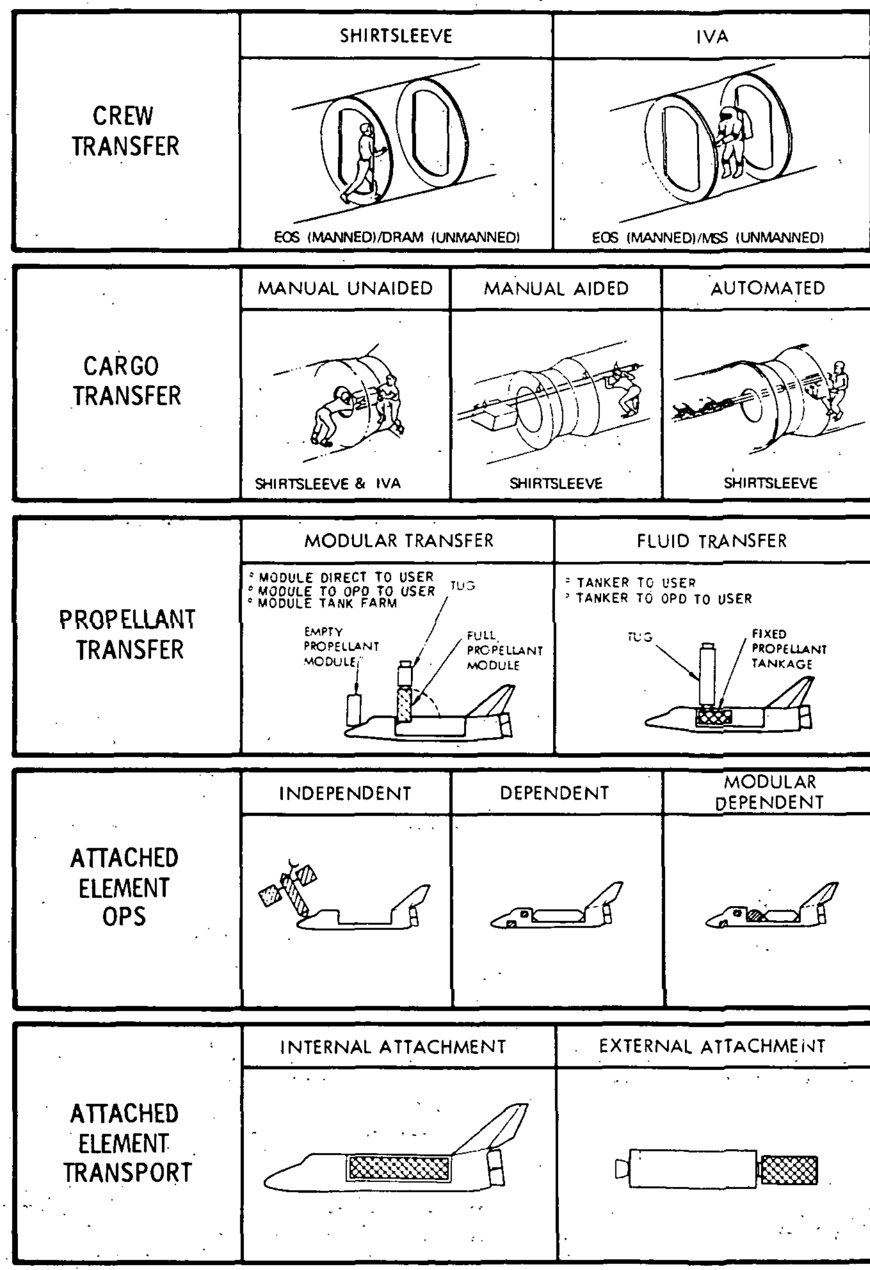


Figure 1-10. Support Operations Activity Group Approaches

OPERATIONAL PROCEDURES

Thirty-eight separate operational procedures were developed to derive functional requirements for the alternate approaches and specific vehicle element paris. These procedures are summarized in the separate Volume II reports. The detailed step-by-step procedure and the rationale for each operation are contained in Appendix B.

Figure 1-11 shows the identification of the procedures for each of the 14 Interfacing Activities.

Volume II, Part 2	
MATING (1) Direct manual dock (2) Manipulator (3) Direct automatic dock ORBITAL ASSEMBLY (1) Shirtsleeve assembly (2) IVA assembly (3) Automatic assembly	SEPARATION (1) Jet translation (manned-to-manned) (2) Manipulator (3) Jet translation (unmanned-to-unmanned) EOS PAYLOAD DEPLOYMENT (1) Manipulator (2) Pivot mechanism EOS PAYLOAD RETRACTION (1) Manipulator (2) Pivot mechanism
Volume II, Part 3	
COMMUNICATIONS (1) Element to ground - direct (2) Element to ground - via TDRS (3) Element to element RENDEZVOUS (1) Passive element in control (2) Active element in control (3) Ground or space control	STATIONKEEPING (1) Autonomous (2) Ground-controlled DETACHED ELEMENT OPERATIONS (1) Ground control - MSFN (2) Ground control - MSFN and data relay (3) Ground control - TDRS (4) Element to element
Volume II, Part 4	
CREW TRANSFER (1) Shirtsleeve (2) IVA CARGO TRANSFER (1) Manual unaided - shirtsleeve (2) Manual unaided - IVA (3) Manual unaided - EVA (4) Manual aided - shirtsleeve (5) Fluid (plumbed) - shirtsleeve	PROPELLANT TRANSFER (1) Direct fluid (2) Direct modular ATTACHED ELEMENT OPERATIONS (1) RAM operations (2) Service and checkout (3) Quiescent storage ATTACHED ELEMENT TRANSPORT (1) Internal or external

Figure 1-11. Operational Procedures

FUNCTIONAL REQUIREMENTS AND DESIGN CONCEPT MODELS

Both qualitative and quantative requirements were developed for each of the alternate approaches and for all possible element pair interfaces identified. These requirements were developed utilizing the step-by-step Operational Procedures and Design Concept Models. Models were created to establish a given set of design capabilities so that an assessment of design impacts could be determined.

In some instances more than one design model was synthesized. Figure 1-12 illustrates three alternate payload retention concepts that were developed and evaluated against all element pairs.

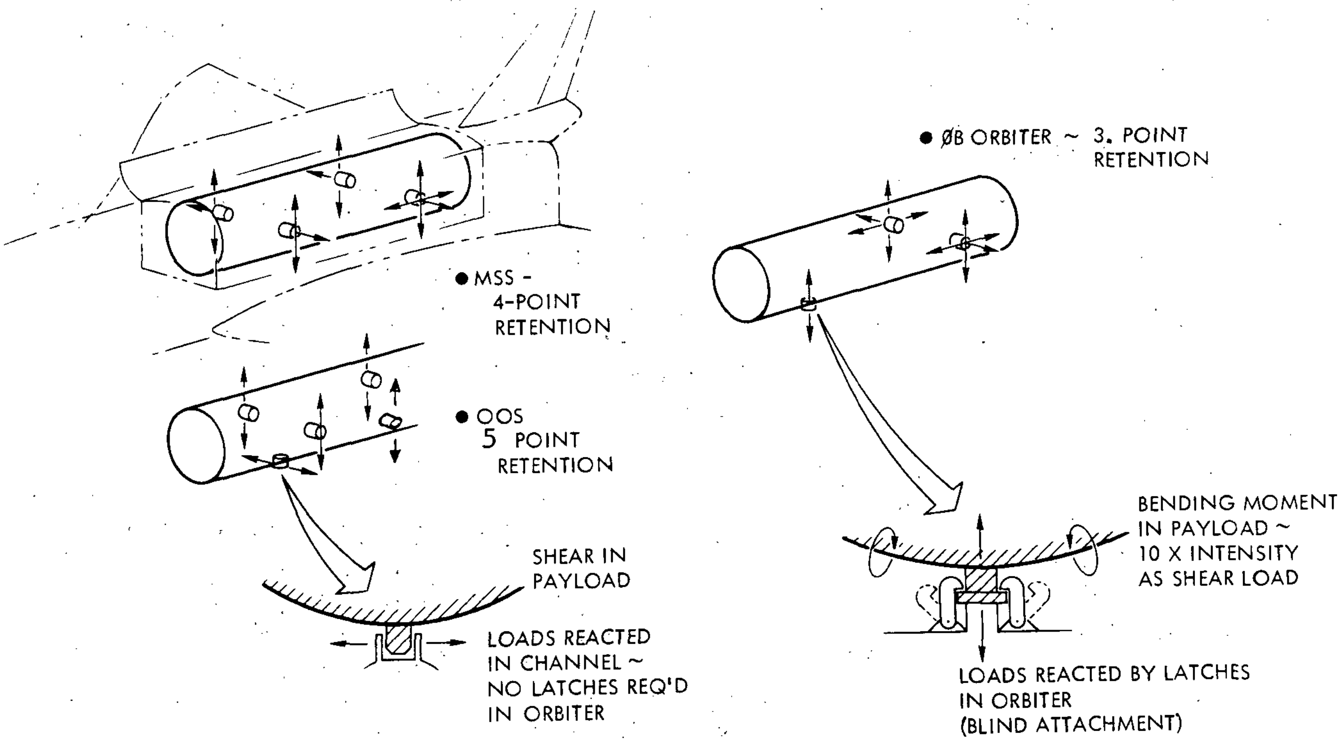


Figure 1-12. Design Concept Model Example

DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

Each of the alternate approaches and the various design concept models were evaluated for applicability to all element pairs. The following is a listing of the types of evaluation criteria that were employed in the evaluations:

- Commonality
- Functional Requirement Applicability
- Technology Status
- Safety
- Reliability
- Relative Cost
- Operational/Design Complexity
- Near-Term Bias
- Far-Term Bias
- Interface Complexity

Figure 1-13 is an example of the resulting payload retention concept selection for one of the elements (EOS). This selection resulted from the application of the criteria to the concepts of Figure 1-12. The design influences that led to this selection and those for all interfacing activities are summarized in sections 2.0, 3.0, and 4.0 of this document and detailed in Volume 2, Parts 2, 3, and 4.

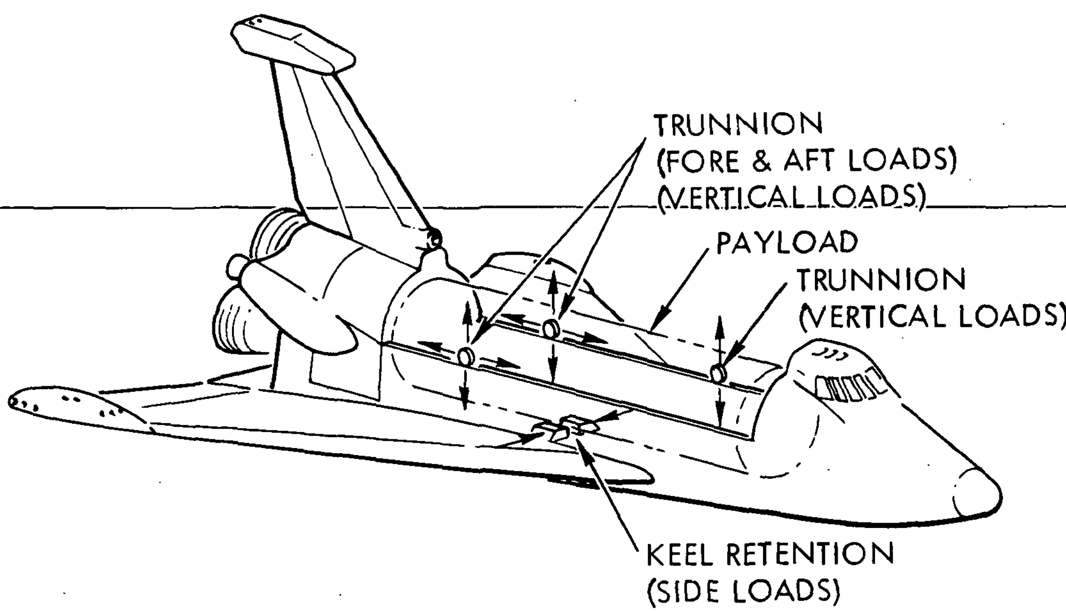


Figure 1-13. Preferred Approach Selection Example

SECTION 2. STRUCTURAL & MECHANICAL ACTIVITY GROUP SUMMARY

This section is an extraction and a condensation of the significant analysis results from the following 5 interfacing activities.

- o MATING
- o ORBITAL ASSEMBLY
- o SEPARATION
- o EOS PAYLOAD DEPLOYMENT
- o EOS PAYLOAD RETRACTION AND STOWAGE

The detail trades and analyses for each of the above interfacing activities are contained in Volume II Part 2 supplemented by Appendix A and Appendix B.

Five topics will be used to convey the pertinent study results:

- . Alternate Approaches
- . Design Concept Models
- . Functional Requirements
- . Preferred Approach Selection
- . Design Influences

A separate commonality analysis study conducted and documented in Appendix A2 concluded that the EOS Payload Deployment and EOS Payload Retraction and Stowage activities could be combined in that the alternate approaches were identical. A common procedure was prepared and the preferred approach selection was conducted considering all functional requirements and design influences of both activities. Therefore this summary will treat the two interfacing activities as one combined activity.

An additional interactivity analyses was conducted to evaluate the potential usage of a manipulator for all of the interfacing activities in this group. The results of that separate analyses are detailed in Appendix A5 and summarized in this section under the mating paragraph (2.1).

STRUCTURAL & MECHANICAL GROUP SUMMARY

DESIGN INFLUENCES	DRIVERS	
	PRIMARY	SECONDARY
DIRECT DOCK • 100-400 FT-LB ATTENUATION • $\leq$0.4 FT/SEC CLOSING VELOCITY • COMMON MATING PORT	MATING	ORBITAL ASSEMBLY SEPARATION
AUTOMATED DOCKING/UNDOCKING • LASER RADAR • PASSIVE REFLECTORS • TV (UNMANNED-TO-UNMANNED	MATING SEPARATION STATIONKEEPING	RENDEZVOUS
PAYLOAD HANDLING • PIVOTAL MECHANISM • MANIPULATOR (EOS ONLY)	MATING EOS P/L DEPLOY ORBITAL ASSY.	EOS P/L RETRACT & STOWAGE
EOS PAYLOAD RETENTION • 4-POINT COPLANAR • KIT CLAMP OR HINGE (SELECTED PAYLOADS)	EOS P/L RETRACT	ATTACHED ELEM TRANSPORT
PAYLOAD EGRESS • EOS AIRLOCK KIT	EOS P/L DEPLOY/ RETRACT AND STOWAGE	CREW TRANSFER CARGO TRANSFER
SATELLITE CAPTURE • SIMPLE MANIPULATION (EXTENSION/RETRACTION)	MATING	CARGO TRANSFER

The more significant conclusions pertaining to the structural/mechanical group interfacing activities are summarized on this chart. Automated direct dock is the preferred concept for mating. Satellite capture will require an adapter between the standardized docking port and the satellite attachment point.

The broad range of configurations that will be delivered to earth orbit by the EOS do not lend themselves to a singular design concept for retention, deployment or retraction. Both the manipulator and the pivoted mechanism are recommended for development. Multi-attachment points are recommended. From purely an interfacing operations standpoint the current traffic modes for the EOS do not warrant inclusion of an airlock in the integral design of the orbiter.

2.1 MATING

The mating activity includes precontract, contact, and post-contact events. Precontact events include alignment of the mating vehicles and reduction of relative velocities. Contact includes capture, impact energy attenuation and relative velocity nulling. Post-contact events include transposition and berth (for the case of manipulator utilization), draw down of the interfaces, structural alignment and rigidization, and interconnect of interfacing utilities.

ALTERNATE APPROACHES

Three generic concepts were initially considered to be viable options for mating: (1) direct docking, (2) extension-retraction capature mechanism, and (3) manipulator berthing. Each of these approaches were also candidates for employing manual controlled automatic/remote controlled techniques.

Figure 2-1 illustrates the three approaches selected for in-depth analyses:

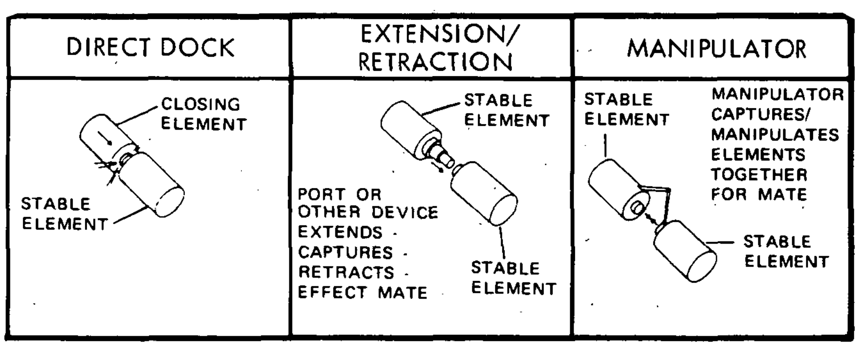


Figure 2-1. Alternate Approaches for Mating

Direct Docking

The "historical" approach to docking consists of flying one vehicle into the other to make contact at a docking interface. The docking interface must then be designed to control the collision by absorbing the impact energy, effecting a capture to prevent rebound separation, and force alignment of the two vehicles. Rigidizing of the two vehicles in the docked position is accomplished by providing a draw down or shock absorber retract capability, such that a series of rigidizing latches engage the opposing docking port to structurally hold the vehicles together.

A classical example of a manually controlled impact docking is the Apollo docking maneuver. The Russian Salyut docking maneuver is an example of an automatic/remote-controlled impact docking with similar functions as that of the Apollo docking system. The Russian example illustrates that even though the spacecraft is manned, automated control of the approach to docking contact can be provided by electronic alignment, range, and range rate sensors if found desirable.

Extension-Retraction

Rather than flying two free-flying vehicles together to accomplish mating, a docking concept that can extend or reach out to the other vehicle and effect capture can avoid high-energy impacts. The extension-retraction mating concept has two elements stationkeeping within close proximity of each other, aligning docking ports, stabilizing, and maintaining attitude control. A docking probe is extended from one of the ports and is captured by the other port. The probe is then retracted, pulling the vehicles together into a hard mate. Probe lengths and stowage problems tended to make this device less universal than the other concept. Because of these two problems and because this concept is essentially a single degree of freedom manipulator subject to the same requirements and procedures as a multiple degree of freedom device, the mating activity did not independently analyze this concept.

Manipulator

The dexterity and low momentum of the manipulator, compared to maneuvering the entire vehicle for direct docking, permits a low-energy capture. Beyond the capture phase, however, the manipulator must provide the same functions as the direct dock concept. It must force alignment of the two vehicles, draw them together in the berthing mode, and seat the vehicle interfaces so that latches actuate to hold the vehicles in position.

The "classical" example of manipulative operations are those found in the handling of radioactive elements of deep-sea vehicle applications, where the manipulator acts as an analog of human arms in an environment totally hostile to the human. At present, their application to space activity is the subject of intense study. Historically, manipulators have been operated manually by a human operator. Computer-aided control has been used to assist the manipulator in achieving near-human dexterity. Some examples exist where the initial deployment and the final stage of stowage of manipulators have been automated. The next step is fully automated manipulator operations with manual remote control override capability. An attractive application of manipulators to unmanned spacecraft mating then becomes apparent. Manipulators include single degree of freedom devices and multiple degree of freedom devices.

The multiple-degree-of-freedom device is more complex; however, it has the flexibility of performing operations other than mating (i.e., assembly and cargo transfer). Whereas, the single-degree-of-freedom manipulator must be located at each port, the multiple-degree device can optionally be located at any single position on an element (the criteria being arm length and number of degrees of freedom).

DESIGN CONCEPT MODELS

Applicability of the mating concepts to the array of study elements required that a series of hardware design models be selected or developed for the following major hardware items:

- Mating Port
- Manipulator
- Alignment and Range/Range Rate Determination Aids
- Electrical/Fluid Line Interface
- Communications

The subsequent paragraphs briefly present the design concept models established for each item.

Mating Port

With the variety of vehicles that future spacecraft must be capable of mating with it is desirable,and in some cases a firm requirement that dockings can be accomplished without the limitation imposed by male and female docking mechanisms. Therefore, a neuter (or androgynous) docking concept that allows space vehicles with similar or identical docking hardware to dock has been selected for the mating port docking model. In addition to the androgynous requirement, several other criteria that are considered primary design requirements on the mating port were identified. These are listed as follows:

1. Provide an unobstructed clearance within the confines of the mating port for routine crew and cargo transfer.

2. Be applicable to a wide variety of spacecraft configurations and mass properties.

3. Provide a structural and dynamic attachment between elements capable of withstanding maneuvering or attitude control loads applied by logistics vehicles.

4. Provide area for utilities interconnections of both permanent and temporary type.

5. Provide a sealed interface after mating to afford a shirtsleeve environment for crew transfer.

6. Have inherent or built-in redundancy.

7. Provide the capability of being maintained in a shirtsleeve environment.

The initial screening of concepts utilizing these criteria, resulted in the elimination of all candidates with the exception of the following:

Multiple Probe and Drogue
Multiple Forks
Ring and Cone
Square Frame

For this study, the ring and cone was selected because of two qualities that make it a slightly favored candidate for universal applications. These are that the ring and cone can be maintained in a shirtsleeve environment with a smaller tunnel than the other concepts and the ring and cone provides for multiple interval rotational oriented mating.

An extensive trade study (see Appendix A, Trade 8) was conducted in parallel with this effort to select the preferred concept if weight and cost and shirtsleeve passage were the only criteria. The results of this trade was the selection of the square frame. This trade also included in its analyses the international docking concept which is essentially a ring and cone design with alignment rods replacing the alignment wedges of the ring and cone. This design makes the international concept more competitive weight wise.

Figure 2-2 shows the general configuration of a ring and cone docking port. The illustration shows a neuter configuration where the active port engages a passive port. The active port can engage another active port thus the androgynous requirement is satisfied. If the EOS Orbiter were the only logistics vehicle in the program, then active-passive concepts would be acceptable. But, once a Tug vehicle or other logistics vehicle which may be required to mate with the EOS orbiter as well as other program elements is included in the program, an androgynous design, multiple ports, or docking adapters are required.

The active port contains the attenuation device, the alignment wedges and alignment wedge guides, while the passive port has alignment guides only. The alignment wedges act as figures that are tapered so that the approaching ring's alignment guide will mesh with it. The intermeshing, tapered wedges and guides provide radial and angular indexing capability. The wedges and guides also provide final alignment and shear capability. The active ring contains independently operating, automatic capture and rigidizing

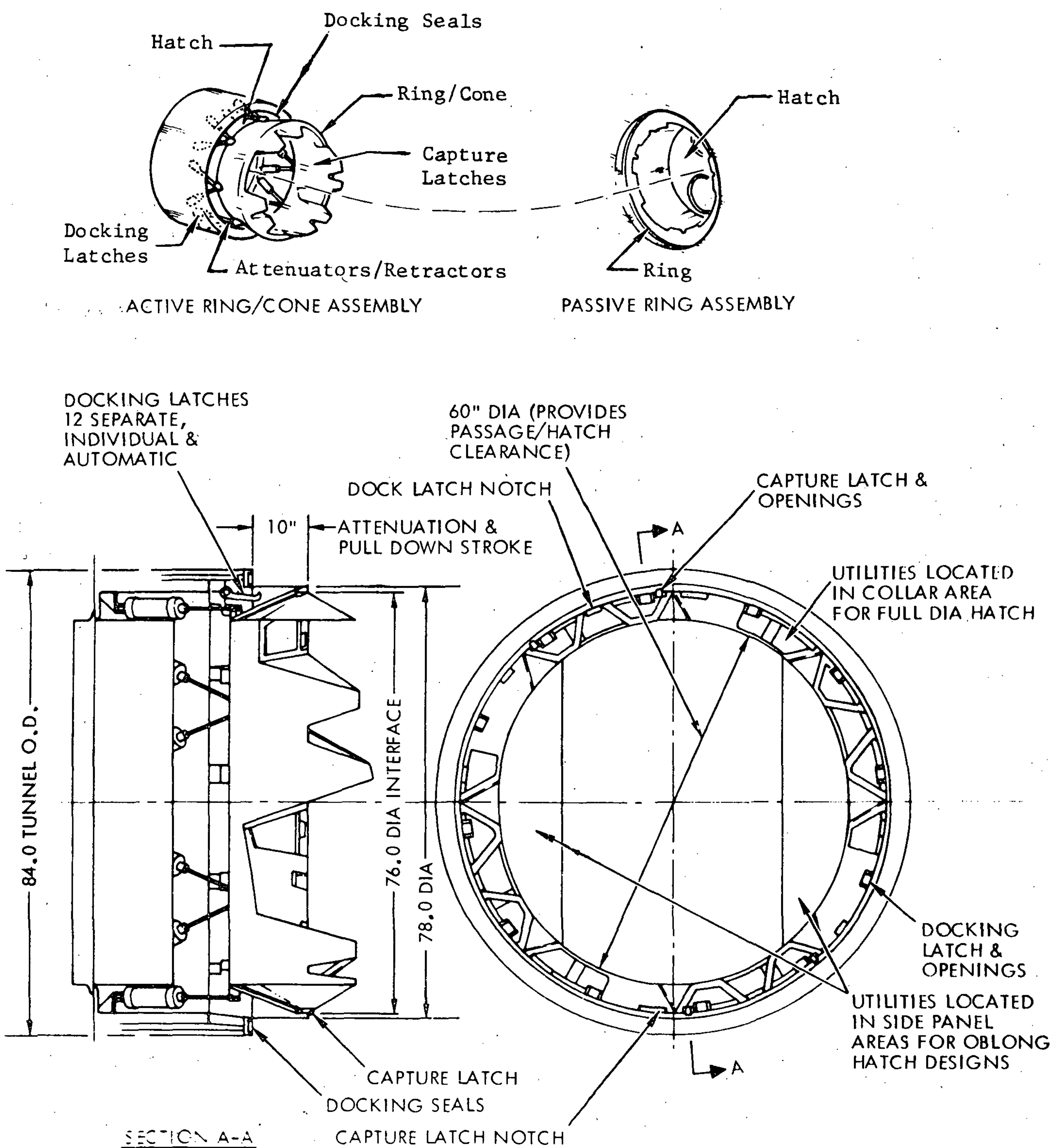


Figure 2-2. Ring and Cone Mating Port Model

latches. The latches are tripped upon contact of the two berthing rings. The latches provide the pull down and clamping force necessary to accomplish the final sealing and structural continuity between the two modules. For module separation, the berthing latches are individually power released and automatically reset for the next berthing engagement.

Sealing of the interface is accomplished with dual seals on the face of the active ring. The passive port ring provides the berthing seal surface. The seals are the only components of the design that are not accessible in a shirtsleeve environment. Consequently, the active ports shall be placed on the vehicles that are returnable to ground such that the seals can be inspected and replaced if necessary.

This mating port design appears viable for all of the study elements, except small satellites. These elements would be penalized if they had to include hardware of this large size unless all future satellites were designed with a common package concept which included the mating port. However, if this is not the case, the probe and drogue utilized on the Apollo could be employed for the docking port concept. Figure 2-3 illustrates the probe and drogue design attached to the androgynous mating port. The difficulty with this concept is the attachment of the probe and drogue to the mating port. With a manipulator, this can easily be accomplished. But, if a manipulator is available, the probe and drogue would probably not be required. Therefore, the probe and drogue concept is only valid for direct docking to a satellite. Installation must be by IVA through the androgynous docking port. This should impose no difficult problem, in that the Apollo concept also required installation and removal. The attenuation device of the probe and drogue would not be required in that the probe would be mounted to the ring of the ring/cone which includes attenuation. Also, the pull down employed on the Apollo probe and drogue would not be required.

Manipulator

Figure 2-4 depicts the manipulator design utilized for the study model. The design incorporates a seven axes arrangement which allows the upper arm and forearm links to be positioned and operated in essentially any desired plane. During docking the seven axes system can control all degrees of relative motion between the vehicles.

The manipulator can be directly controlled manually, it can be computer controlled, or it can be remotely controlled. The assembly consists of upper and lower structural elements, pivot joint actuators, and the wrist mechanism. The arm carries a remote control TV camera and spotlight mounted near the terminal end of the arm. Dual torque motors are provided and designed such that the failure of one motor does not prevent drive by the other.

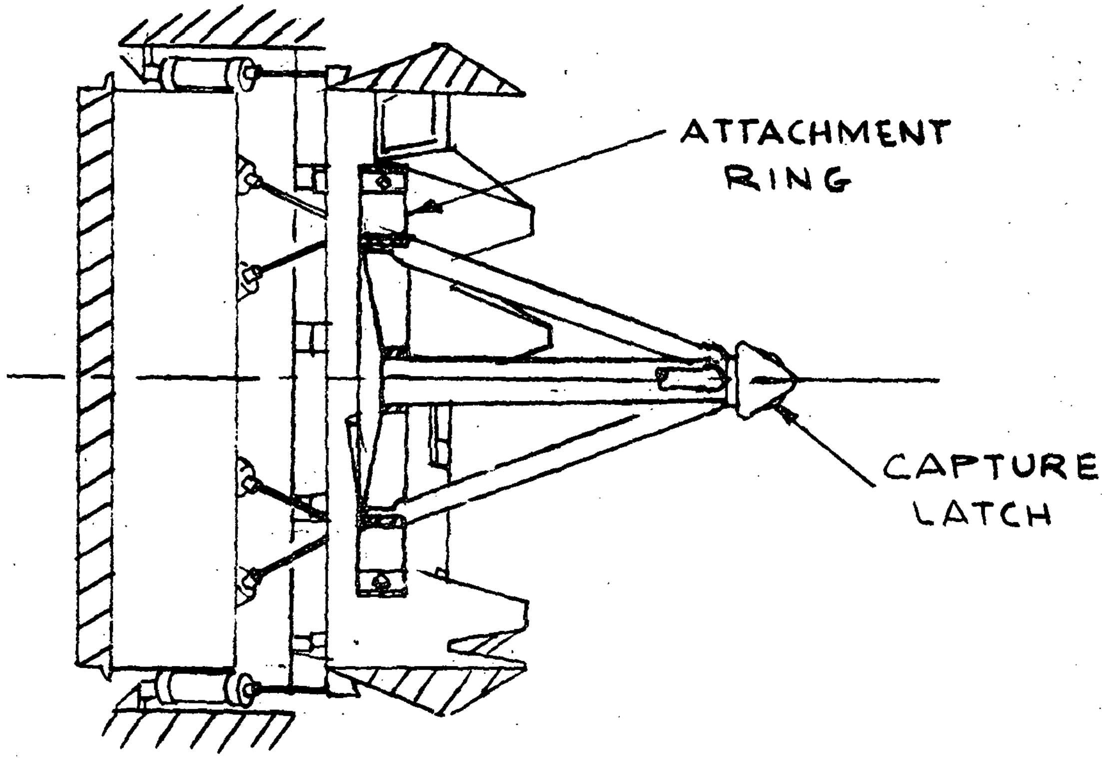


Figure 2-3. Ring Design with Apollo Probe Attached

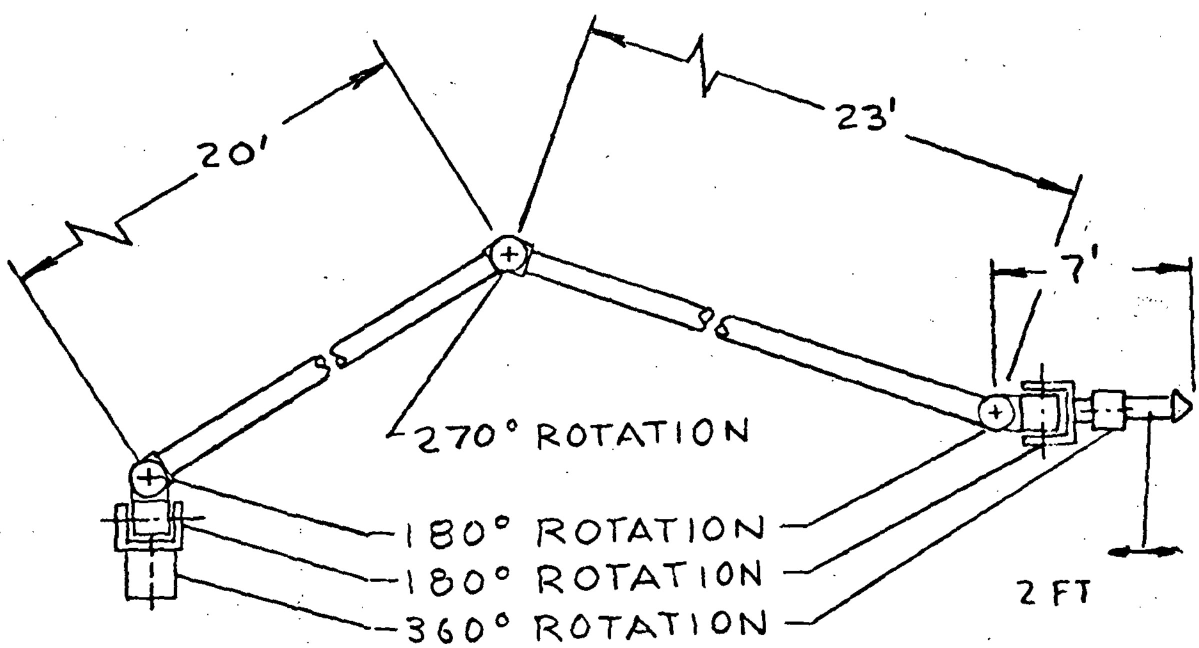


Figure 2-4. Manipulator Concept Model

The manipulator concept is readily adaptable to mating operations between the EOS orbiter and satellites with virtually no penalties on either the EOS orbiter or satellites. However, mating operations between tugs and satellites with a manipulator have operational constraints. A fully automated mating between two stationkeeping elements via a manipulator is a marginal concept. It is considered mandatory that a man be in the control loop. Remote control via RF link (including TV) are required for unmanned tug - satellite operations.

Alignment and Range/Range Rate Determination Aids

Because both visual alignment concepts and laser radar systems are considered viable candidates with the selection possibly dependent on the mating method (direct dock or manipulation), models have been developed for both options. The visual alignment concept would probably be the selected method for manipulator operations, whereas, for direct docking, laser systems will be employed utilizing visual backup. The laser radar concept was selected as the preferred tracking approach for rendezvous operations and since the mating operation begins at termination of rendezvous it would be natural to extend laser radar utilization to determine alignment and range and range rate criteria for the docking operations.

For manipulator operations, if the manipulator is automated (computerized), the alignment and range/range rate determination problem is associated only with the capture of a target vehicle. With a TV camera located at the terminal end of the manipulator transmitting pictures to the control center, alignment becomes a visual judgment task. The vehicle rates are nulled until a low limit cycle deadband is achieved between vehicles. The controller then needs only to direct the end effector into the capture receptacle making small corrections as the manipulator tip approaches the receptacle. The more difficult task may be to manipulate the associated joints such that manipulator arms do not come in contact with appendages of the target vehicle. With a second manipulator, this hazard can be reduced by strategically locating the second manipulator so that it's TV camera can view the working manipulator arms as illustrated in Figure 2-5.

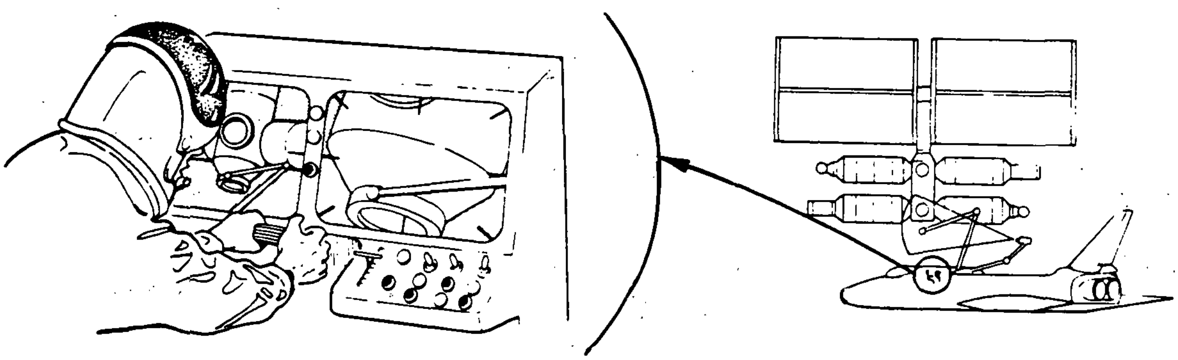


Figure 2-5. TV-Manipulator Interface

Vehicle standoff position (range) during the capture can afford a relatively wide tolerance (i.e., a 30-foot standoff position can accept +/-5 foot tolerances without imposing any hazard). The separation distances can be estimated by extending the manipulator arm and using it as a measure of the range between the vehicles. Relative velocity can be determined by maneuvering the end effector relatively close to the capture target (less than 10 feet), than stopping the arm and viewing the capture target for movement. When no movement is detected, the capture is performed. Simulations utilizing this technique have shown that the relative velocity can be nulled consistently by the pilots to less than 0.1 foot/second. The capture, in fact in most cases is made when the relative velocity is approaching 0.03 feet/second which is almost as close a tolerance as laser radar systems provide.

Direct docking alignment and range rate can be determined very accurately, when man is involved, using only visual aids. However, when docking two unmanned vehicles, visual techniques cannot be employed unless the vehicles are under full remote control. If remote control is utilized the control center (ground or another element) would be receiving a TV picture of the docking very similar to what would be seen by a pilot if the vehicle were manned. The control center would then remotely fly the vehicle into a hard dock.

With a laser radar system, fully automated dockings become a reality. The laser radar will provide precise information on the closing rates of vehicles, real time range data, and the angular alignment between vehicles. This data can be assimilated in a control system computer and resultant commands transmitted to the required thrusters such that a precision docking will be accomplished. During a direct docking, the laser radar onboard the vehicle continuously measures the line-of-sight angles. The line-of-sight geometry is shown in Figure 2-6. The line-of-sight angles must be nulled usually to approximately +/-3 degrees, or less. Another measurement that is critical to a successful docking is the closure rate. Both the range rate and angle rates must be continuously and accurately measured so that the contact velocities can be carefully controlled prior to and at docking impact.

Before any docking attempt is made, the relative attitudes of both elements must be determined such that successive maneuvering can roughly align the opposing mating ports and the laser radar can acquire the docking target reflectors. A method has been conceived where relative attitude between vehicles, and the mating ports can be aligned utilizing a laser system. The concept employs a search routine, whereby the active vehicle maneuvers around the passive target at some specified range. During the maneuvers the laser searches for a particular reflector pattern. When this pattern is recognized (minimum of three reflectors) and attitude determined, the vehicle moves to align the ports. Since the target is arbitrarily oriented at a fixed attitude, reflectors must be located so as to be in view of the active vehicle laser beam from any position. If the payload is cylindrical in shape, with no interferring protrusions, the pattern might

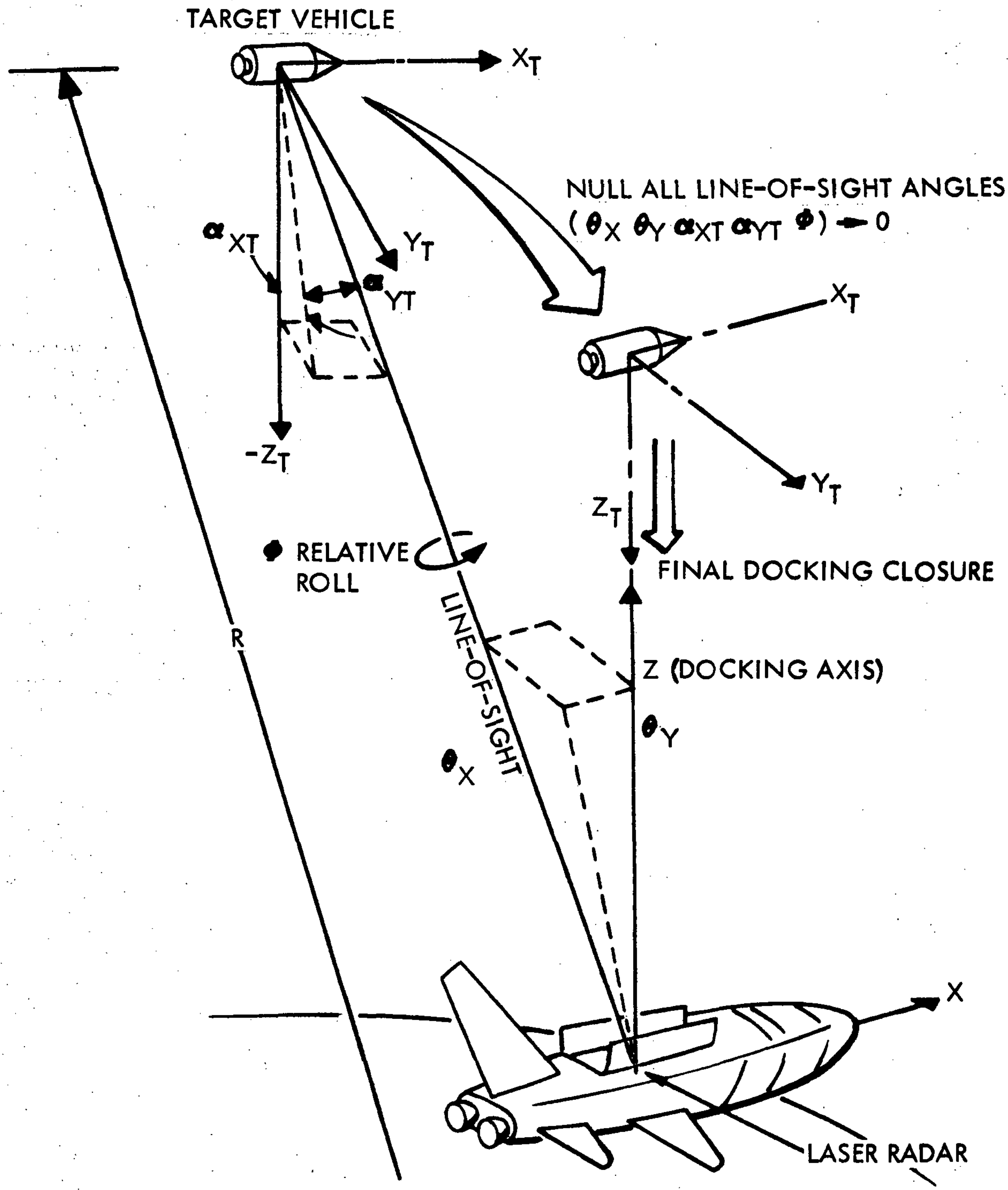


Figure 2-6. SCR Target Acquisition and Tracking

appear as shown in Figure 2-7. Reflector placement becomes more critical with an irregular-shaped vehicle or with vehicles with interfering protrusions such that multiple patterns must be developed and tailored for the particular configuration. This method of identifying passive laser reflectors and utilizing this knowledge to align the active vehicles along the payload docking port centerline for final approach appears feasible. However, if a remote control center is available to transmit maneuvering commands to one or both vehicles, the attitude determination and initial alignment can be accomplished much more readily and within the present technology utilizing a TV camera on the active vehicle. The camera could be remotely controlled to scan the vicinity of the active vehicle until it located the target vehicle. Whereupon, it would be locked on target. The relative position of the vehicles could be determined by reading the slew angle of the camera with respect to the active vehicle attitude. Relative attitude can be determined, either by directly viewing the target vehicle and it's appendages or by viewing an active light pattern on the target vehicle. The active or passive vehicle could then be commanded to assume an attitude that would align the docking ports such that the laser radar can quickly locate the reflectors that bound the mating port. Because this latter system is within present technology, and because it is highly likely that all unmanned vehicles in the future will have capability of accepting remote commands, this concept is selected for automated docking attitude determination.

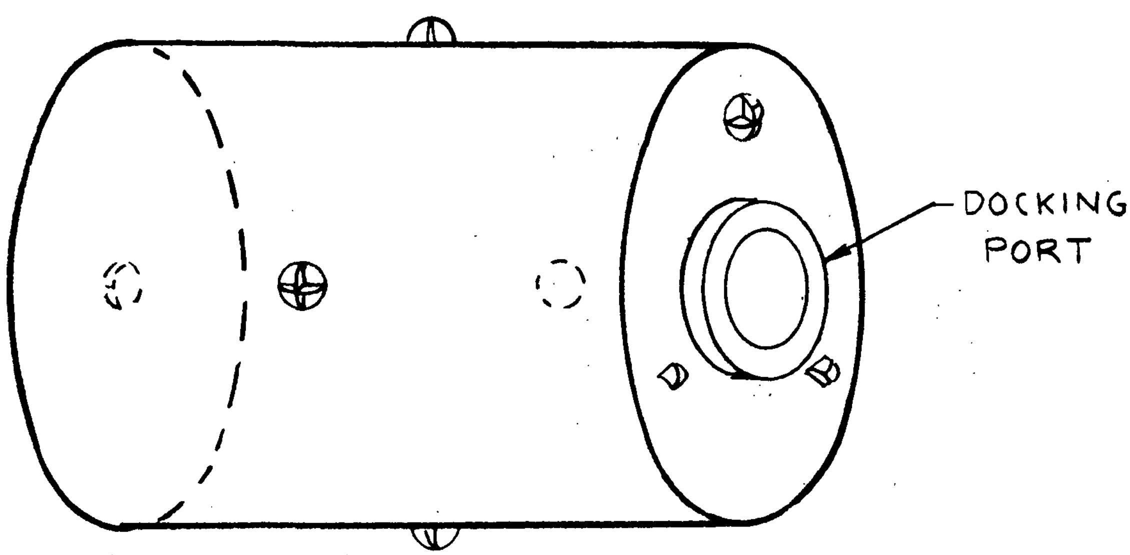


Figure 2-7. Payload Passive Reflector Geometry
for Attitude Determination and Mating Port Alignment

The laser radar concept can utilize either active or passive reflectors. For this model, the passive reflector is selected in that the concept relies on less complexity and interfaces and because the docking criteria does not warrant the additional precision afforded by active reflectors.

For a fully automatic docking, either vehicle can be the active element. It is not necessary for the vehicle with the laser radar to assume the active role. Figure 2-8 illustrates this option for the docking of a module to a space station utilizing the EOS Orbiter as the active vehicle. This concept has the laser radar installed at the docking port end of the cargo module. This is the preferred location in that this location allows for the direct reading of docking port centerline misdistance (and provides the most commonality with respect to laser reflector location). If the laser radar is located within the EOS Orbiter, angular misalignment must be integrated with the geometry of the docking port location with respect to the laser radar location for miss distance determination. The concept has the laser radar data being directly read into the control computer. If however, the laser radar is located on the station, the radar data can be computed onboard the station and control commands transmitted to the EOS Orbiter control computer or the data can be directly transmitted to the EOS orbiter control computer with it performing the computation.

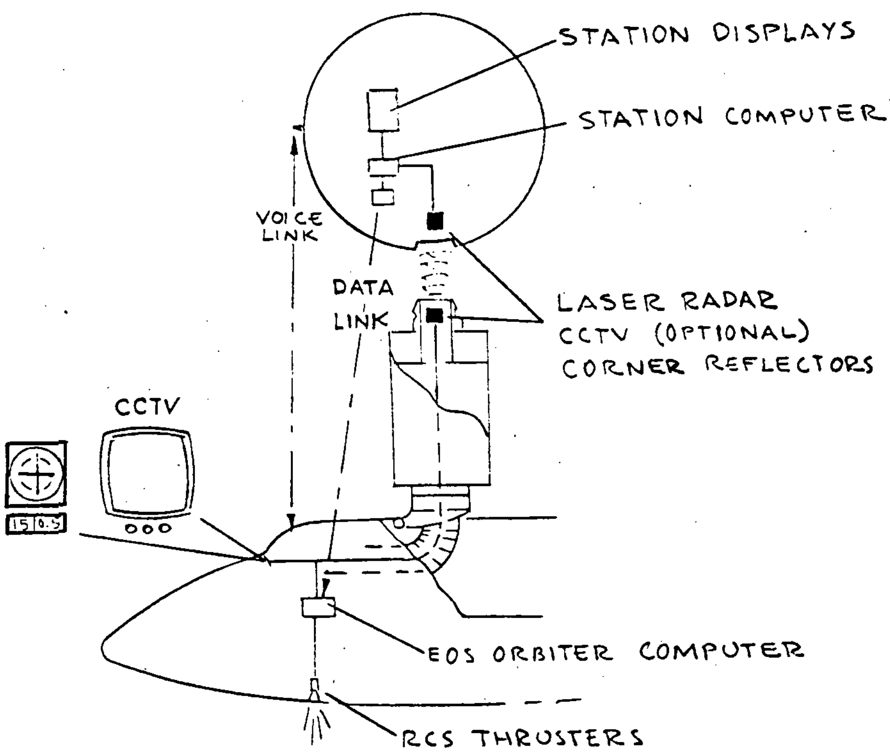


Figure 2-8. Automatic Docking Either Vehicle with Laser Radar

Electric/Fluid Line Interface

Electrical cables and fluid lines that traverse crew and cargo passages shall be suitably enclosed or otherwise protected to minimize hazards to the crew and provide protection for the hardware. The interface between mated elements must be designed to be closed and sealed without performing a prolonged demating of interface connectors.

Figure 2-9 is a design concept model that will satisfy the foregoing requirement. This design is such that no cable or fluid line is exposed to damage within the passageway and the hatches can be sealed without demating the connectors. This design requires that the interfacing lines be connected utilizing short interconnect linkages. The design still requires that the interconnect linkages be removed before separation. However, this operation can be performed IVA or the hatch on the contaminated side of the interface can be sealed, the tunnel repressurized with clean air and the interfaces demated.

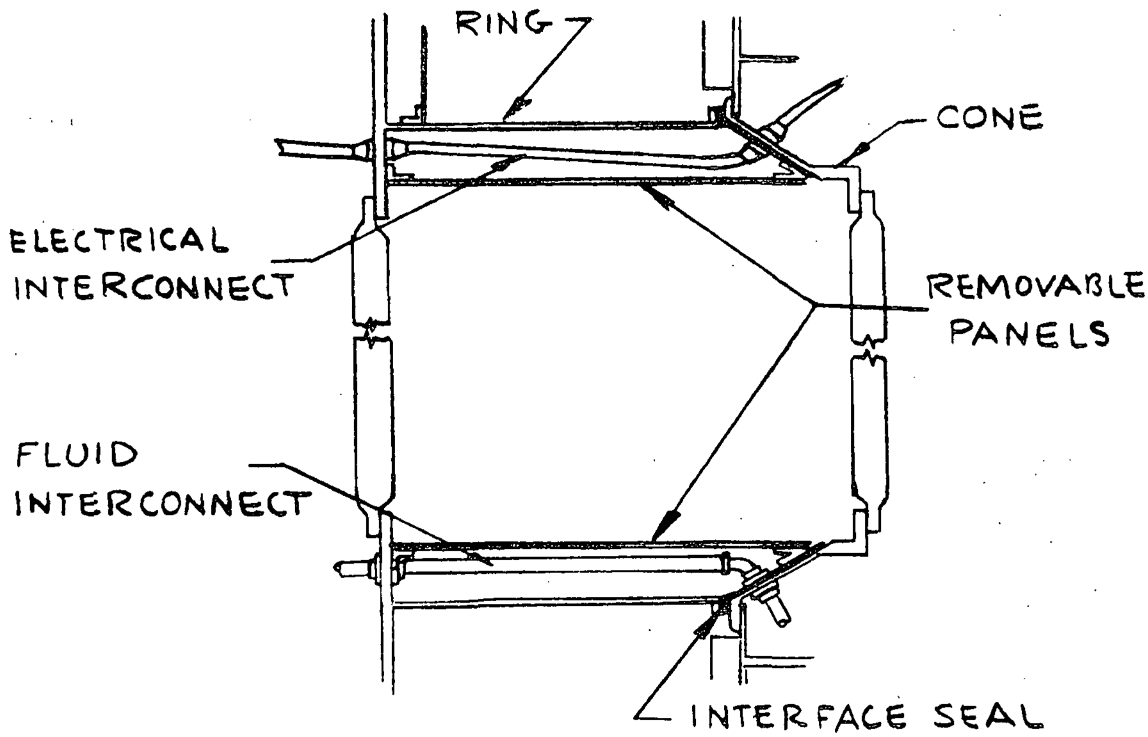


Figure 2-9. Electrical/Fluid Line Interface

COMMUNICATIONS

Figure 2-10 is a model of the RF communications in effect when mating various program elements. Manned vehicles will be conversing directly during dockings, passing information between vehicles over a duplex voice link. Unmanned vehicles require some type of remote control such as commands to assume particular attitudes or to activate particular equipment. Unmanned vehicles must also be statused before and during the mating activity to verify that subsystems are in accord with the mating operation. Remote control centers, such as ground control, can interface directly with orbiting elements during mating when the vehicles are in line-of-sight, however, since this cannot be guaranteed during all matings or for the full duration of the mating, this interface is not considered totally acceptable. Therefore, an interface that utilizes a system such as TDRS is required.

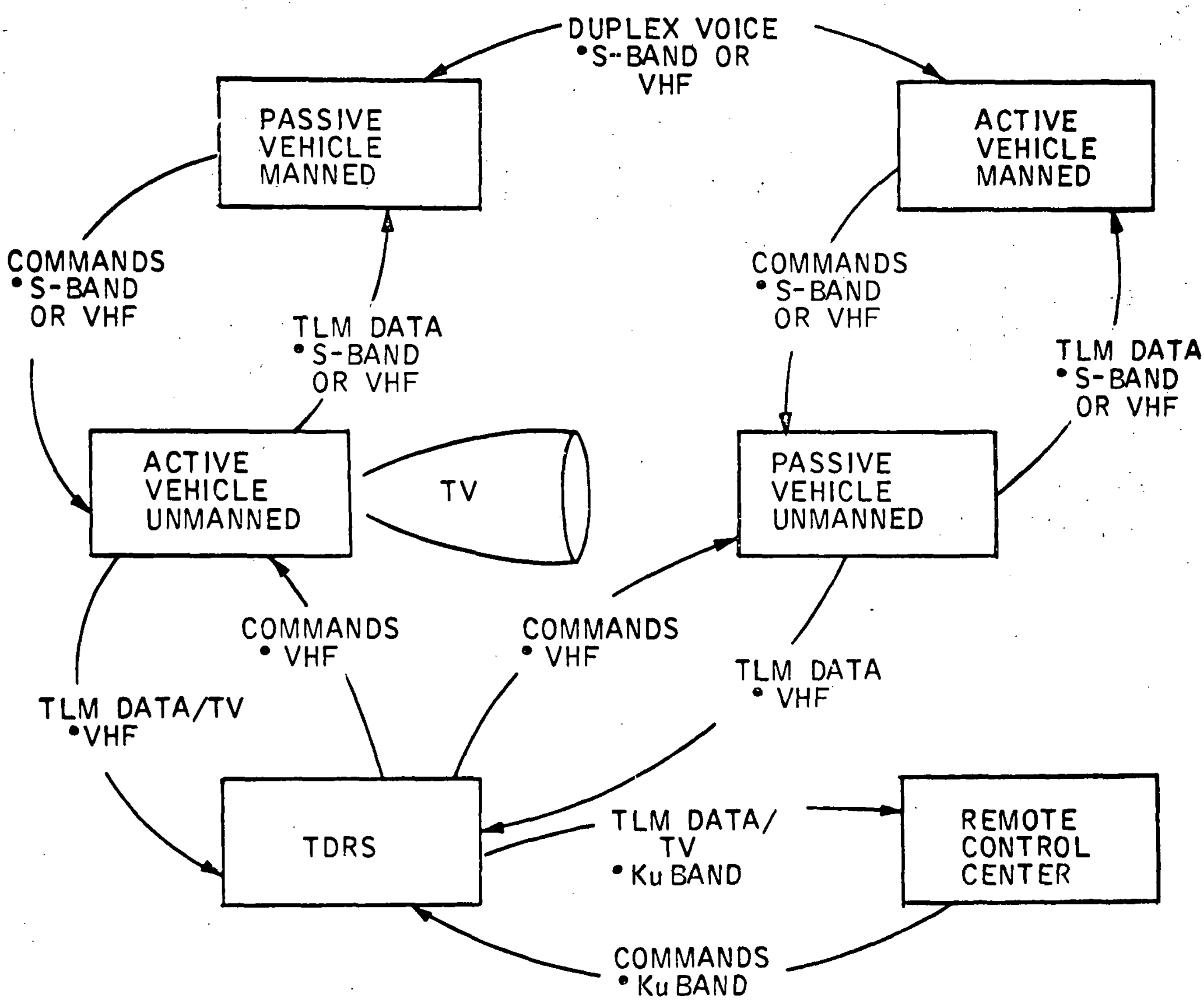


Figure 2-10. Mating Communications Interfaces

FUNCTIONAL REQUIREMENTS

The most significant functional requirements associated with mating are the closing velocities and alignment requirements. These requirements are summarized as follows:

Direct Dock

Longitudinal velocity: 0.2 fps to 0.4 fps

Lateral velocity: 0.09 fps to 0.5 fps

Angular velocity: 0.06 dps to 0.3 dps

Lateral miss distance: plus or minus 6 inches

Misalignment (p. y. r): plus or minus 3 degrees

Vehicle attitude hold: plus or minus 0.2 deg to plus or minus 1.0 deg

Manipulator capture

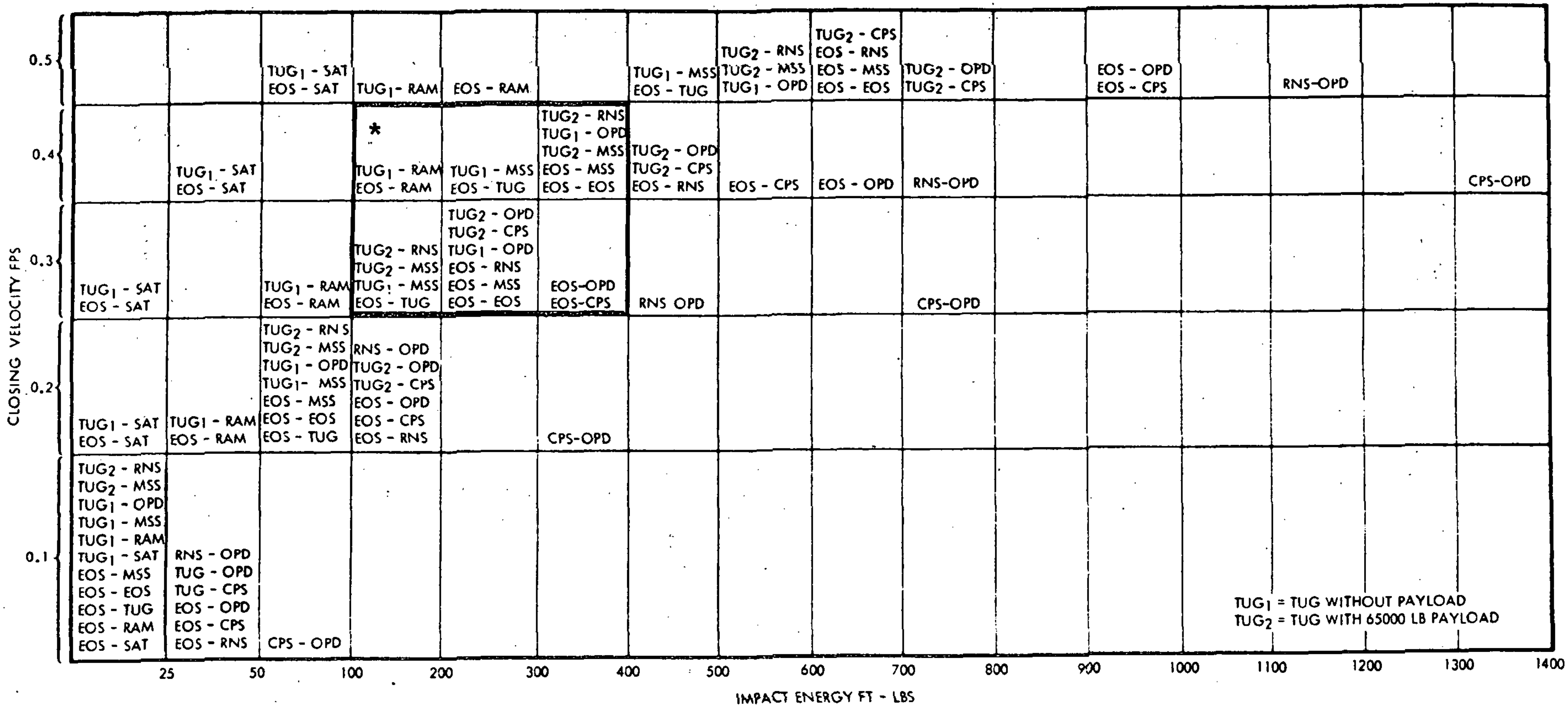
Vehicle attitude hold: plus or minus 0.2 degree

Vehicle rate stabilization: plus or minus 0.05 deg/sec

Additional requirements are applicable for the manual direct concept such as visual/video aids. These requirements were based upon design concept models developed during the course of the analyses.

One of the most important considerations in determining the practicability of the direct dock concept was the evaluation of impact attenuation systems. Equivalent mass characteristics of potential mating elements ranged from as low as 500 slugs (EOS-satellite) to as high as 20K slugs (CPS-OPD). The basic problem was to determine if a common docking concept could be derived that would accommodate this range of equivalent masses in the docking operation. Four docking concepts were evaluated: ring and cone, square frame, multi-probe and drogue, and the international concept. Any of the four could accommodate the mating mass spectrum (with two exceptions) with a singular attenuation design concept provided reasonable closing velocity controls were imposed. Figure 2-11 illustrates the interrelationships between element pairs, closing velocity, and kinetic energy. The emphasized area indicates the preferred design concept. Almost all element pairs can direct dock with a singular attenuation design concept of 100 to 400 ft-lb provided the closing velocity is less than 0.4 fps.

The only exception to the singular concept are the OPD-CPS/RNS and satellite interfaces. The first two are not considered a limitation because the results of the analyses of the propellant transfer activity indicated that an OPD was not a required nor recommended orbital element. Satellites require unique handling because of their characteristic size. It would be unrealistic to impose the incorporation of a standard docking port on a satellite that could actually be smaller and lighter than the docking mechanism.



*Emphasized area represents the best fit for commonality. All element pairs can be direct dock with a system that attenuates 100 to 400 ft-lb impact energy if closing velocities are maintained at less than 0.4 fps.

Figure 2-11. Energy Attenuation Criteria for Direct Docking Various Element Pairs

PREFERRED APPROACH SELECTION

Two generic approaches to mating have been considered, direct dock and manipulator berth. Direct dock includes manual and automatic techniques. Manipulator berth is applicable to manned operations only. If a manipulator is in the program, direct dock will still be required at least for the unmanned-to-unmanned vehicle matings. If direct docking along was considered, the conceptual design evaluation would be to select between automated techniques and manual techniques. If manual techniques were selected, automated concepts would still be required for the unmanned-to-unmanned vehicle matings.

Although manipulators are new in the space program, various forms have been used extensively in earth-bound hazardous environments; e.g., under water, radiation environments, etc. Admittedly extensive development is required but manipulators are not considered beyond the state of the art. However, certain limitations were assumed in evaluating the manipulator. They were:

1. The dynamics problem associated with mating an element attached to the extended manipulator to a close proximity stationkeeping element (the "plug in" concept) would impose unrealistic structural and control requirements on the manipulator.

2. Structures and dynamics limit the total length of the manipulator to 60 feet.

(Evaluation of all the element pairs that will conduct mating operations indicated that neither of these manipulator assumptions would preclude its use.)

3. Automated/unmanned manipulator operation was not practical.

4. Remote control from ground of manipulator mating was not practical as a normal operation because of the potential long duration gaps/short duration contact characteristics of the communication links.

Comparison of these characteristics for the manipulator and direct dock concepts in light of all the element pair mating interactions indicated that at least a hybrid concept was required. Direct dock was required for unmanned element matings; manipulator concepts were required for satellite matings. Thus, the preferred approach selection was which concept should be the baseline and which concept should be considered a "special situations" application.

Table 2-1 summarizes the basic considerations of the concepts. Manual dock is the preferred baseline. Automatic direct dock closely approximates the manual concept. The one major unique additional requirement for the automatic concept is the necessity of accurate range, range rate, and alignment data. The laser scanning radar can provide the necessary accuracies. Also video observation of the operation would be required.

Table 2-1. Mating Concept Comparison

Factors \ Concepts	Direct Dock: Manual	Direct Dock: Automatic	Manipulator Berth
Technology	Preferred - state of the art	Acceptable - technology available	Least preferred - new to space
Checkout Maintenance	Preferred - least and less complex parts	Acceptable - with active elements on vehicles that can be manned or returned to ground	Least preferred - requires ground maintenance
Safety	Acceptable	Acceptable	Acceptable
Reliability	Preferred - least parts	Acceptable - with redundant sensors	Acceptable - with redundant arms
Commonality	Acceptable - still requires automatic docking	Preferred - commonality across all element pairs	Least preferred - requires direct docking and manipulator techniques
Relative Cost			
Initial	Least cost	Medium cost	Highest cost
Long term	Least cost	Medium cost	Medium cost
Operational/Design Complexity	Preferred - less operations, least complex hardware	Acceptable - least operations, complex hardware	Least preferred - most operations, complex hardware
Interfaces			
Power	Low	Medium	High
ISS	Low	High	High
ACS	None additional	Complex	Simple
Crew	Vehicle pilot	None required	Vehicle pilot and /or manipulator controller
Near-Term Bias	Preferred	Acceptable	Least preferred
Far-Term Bias	Preferred	Preferred	Acceptable

An overall evaluation of the comparison factors tends to favor the direct dock approach. But, because an automatic direct docking concept must be developed for mating unmanned elements to unmanned elements, it is recommended that for commonality this approach be the primary mating mode for all element pairs. It is also recommended that when a manned element is involved, manual override capability be provided.

The one prime driver for selection of the manipulator is mating operations between logistics vehicles and satellites. However, design alternates to the manipulator concept are available that can effectively perform this mating task. It is recommended that this type of concept be developed for adapting to the direct docking design when required.

DESIGN INFLUENCES

Table 2-2 identifies the hardware for each noted element based on the preferred conceptual approach for mating the various element pairs. The manipulator hardware is included as well as automatic direct dock and manual direct dock backup hardware for the EOS orbiter and applicable elements that mate with the EOS orbiter. Mating ports designed for direct dock can be used for berthing (manipulator approach) with no design modification. The following paragraphs are a synopsis of why each piece of hardware was selected for the identified element.

Mating Port

The elements with active attenuation are the logistics vehicles and the space stations (MSS and OLS), all other elements can be equipped with passive mating ports. Where two mating ports are indicated for an element, it infers that one will be on each end of the element. Note 2 refers to individual assembly criteria where two modules of an assembly must be mated; one of the elements must be equipped with an attenuation device. However, in none of the noted cases do the elements require an attenuation system for other elements mating to them except for the MSS which requires attenuation to support the MSS detached RAM. The satellites (note 1) are not configurationally defined, those that will be directly docked can be equipped with passive docking ports.

Laser Radar Transceiver

The laser radar transceiver is allocated to all logistics vehicles because these vehicles must perform automated dockings. The MSS is equipped with a laser radar to support MSS detached RAM's if they free fly into dock and also to provide a backup capability for docking with the logistics vehicles.

Laser Radar Reflectors

The laser radar reflectors are required on all elements to support those vehicles with laser radars. Some of the elements, for example the EOS orbiter, are equipped with reflectors to provide a backup docking capability with another element.

Direct Visual Alignment Scope

The requirement for a direct visual alignment is imposed only on the EOS orbiter because it is the only vehicle recommended for direct manual backup capability. Other logistics vehicles that may be manned can perform direct manual dockings using the laser radar device.

Visual Alignment Targets

Targets are required on all elements, as noted, to support the EOS orbiter backup visual alignment.

TV Camera

TV to the remote control center is required to support rough alignment of unmanned mating pairs and for inspection of mating ports, and possibly for the EOS backup visual alignment. The TV camera is allocated only to the logistics vehicles.

Translation Capability

All of the logistics vehicles require translational capability to accomplish the dock. The MSS supported detached RAM (Note 3) requires translation capability if it is to free fly and direct dock to the MSS without the support of a logistics vehicle.

Manipulator

As previously indicated, only the EOS orbiter should be equipped with a manipulator.

Manipulator End Effector Receptacle

A manipulator end effector receptacle must be installed on all elements the EOS mates with, thus allowing the option of manipulator berthing or direct docking to effect the mate.

Table 2-2. Mating Hardware Preference

Hardware	Element													
	EOS	UN-MAN TUG	MAN TUG	EOS DRAM	MSS ARAM	MSS DRAM	RET RESUP SAT	EO RESUP MOD	MSS	CPS OIS	CPS CLS	RNS	OLS	OPD
Mating port (w/attenuator)	1	1	1	-	-	-	Note (1)	1	Note (2)	Note (2)	Note (2)	Note (2)	Note (2)	Note (2)
(w/o attenuator)	-	-	-	1	2	2		1						
Laser radar transceiver	-	✓	✓	-	-	-	-	-	✓	✓	✓	✓	✓	-
Passive laser radar reflectors	✓	✓	✓	✓	✓	✓	Note (1)	✓	✓	✓	✓	✓	✓	✓
Direct visual alignment scope	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
Visual aligment targets	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
TV camera	-	✓	-	-	-	-	-	-	-	✓	✓	✓	-	-
Translation capability	✓	✓	✓	-	-	Note (3)	-	-	-	✓	✓	✓	-	-
Manipulator	✓	-	-	-	-	-	-	-	-	-	-	-	-	-
Manipulator end effector receptacle	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Note (1) Configurations are not defined. Size is critical as to whether the satellite will support a docking port or not.

Note (2) These elements can be modularly assembled. Therefore, an attenuation device is required on one or the other interfaces of the assembly.

Note (3) The MSS-supported DRAM requires translation capability if it is to free-fly and direct-dock to the MSS.

2.2 ORBITAL ASSEMBLY

The orbital assembly interfacing activity includes two distinct classes of operations. One is the assembly of modules of elements for orbital operations (e.g., MSS). The other is the temporary assembly of elements or modules of elements on a transport vehicle for subsequent delivery to a higher energy orbit (e.g., OLS modules on a CPS). There are always a minimum of three elements and/or modules involved when the orbital assembly occurs. Two elements being joined together is considered a mating activity. Mating and attached element transport activities are closely related to the orbital assembly activity and directly influence the orbital assembly concepts.

Two major phases of orbital assembly that were considered are (1) "Initial Mating Activities" which involve operation up to and including mate of the elements/modules to be assembled, and (2) "Post Mating Activities" which include supplemental rigidization and utility interconnect operations.

The first phase is essentially a mating operation. The approaches, design concepts, procedures, and functional requirements for this phase of orbital assembly are the same as for mating. The second phase of orbital assembly is dependent upon the subsequent operations of the assemblage. If the assembly is to be an on-orbit operational element (e.g., MSS), then the post capture operations must reflect crew and cargo transfer and attached element operations. If the assemblage is to be transported by a logistics element, then the primary driver on the post capture orbital assembly phase will be the characteristics of the attached element transport operation.

The rigidization portion of the second phase of orbital assembly activity was analyzed in conjunction with the mating and attached element transport activities. Assuming that the direct dock concept or berthing port concept (manipulator) are used, no additional rigidization over and above that which is inherent in the port interlock design was required.

ALTERNATE APPROACHES

Alternate concepts for utility interconnects are illustrated in Figure 2-12.

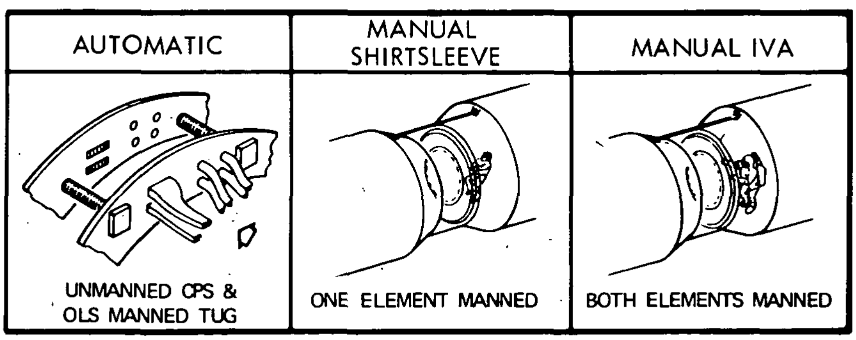


Figure 2-12. Preferred Orbital Assembly Approaches for Post Contact

DESIGN CONCEPT MODELS

As stated previously the first phase of orbital assembly operations through capture is essentially the same as mating operations. The functional requirements and constraints are discussed in detail in Section 1.0. The results of the mating analyses, as they apply to the orbital assembly activity are summarized as follows:

a. The mating activity analyses resulted in selecting an automatic direct docking concept as opposed to the manipulator berth approach. The manipulator approach was rejected primarily because of the higher cost and difficult task of maintaining it. However, if a manipulator is selected for other programmatic reasons, the mating activity preferred that it be allocated only to the EOS orbiter and that the EOS orbiter also be redundantly equipped for direct docking. The mating activity indicated that installing a manipulator on any other element would not provide enough benefits to warrant the additional costs.

b. The automatic direct dock concept provides for the mating of all identified study element pairs using common hardware and is not perturbated if the elements are manned or unmanned. The concept will effectively attach two elements together, structurally align the elements, and where applicable, provide a shirtsleeve passage between the elements. The following paragraphs describe the general characteristics of the models developed for the mating activity.

Mating Port

The mating port model would be a neuter (or androgynous) docking concept that allows space vehicles with similar or identical docking hardware to be docked together.

The mating activity selected the ring and cone mating port for its model. Refer to Figure 2-2 and the text for the rationale.

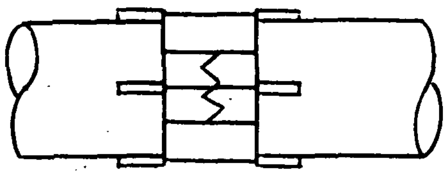
Direct Docking Alignment

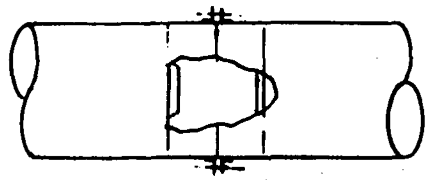
For direct docking, the mating activity selected the laser radar concept as the primary alignment aid. Figure 2-8 shows the interfaces required for the assembly of a module on an MSS using the EOS orbiter as the transporting element. It can be seen that the radar transceiver and corner reflectors are located at the interfacing ports. This is the recommended configuration; however, other locations on elements are acceptable, but they will be less common and require special computation to determine the actual alignment of the mating ports.

Structural Rigidization

The three alternates for post capture rigidization are manual shirt-sleeve, manual EVA, and automatic. Automatic could be an inherent part of the docking hardware or supplemental hardware could be used.

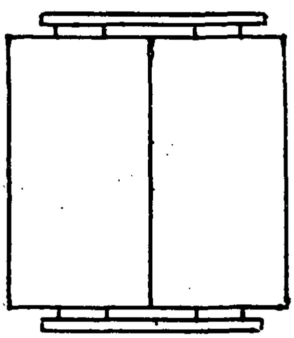
Aumentation and Shell-to-Shell



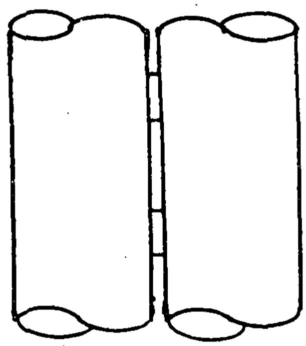


The augmentation concept utilizes supplemental rigid or flexible tension ties connecting the shells of the elements/modules together. It could be mechanized by any of the three approaches. The shell-to-shell concept is a minor variation of the aumentation scheme. It is comparable to connecting two electrical connectors together, only on a very large scale. Again, all three approaches are applicable. Manual jack screws or clamps could be employed or motor driven jack screws with alignment guides could be designed.

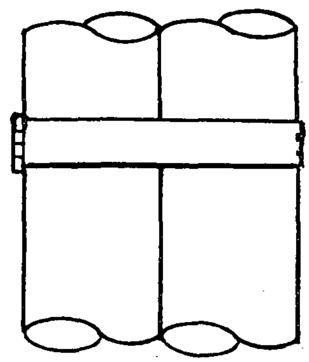
Side-by-Side



TRANSIT



DOCK

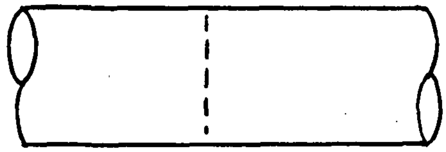


STRAPS

Side by side assembly of elements/modules include two mating concepts and a large Marman clamp concept. The transit concept uses a flat pack multiple docking adapter on the two ends of the modules to be assembled. The major problem with this concept is the alignment tolerances required during the mating process, particularly when the modules are relatively long. This can be alleviated by designing a pivoting transit device such that the modules initially mate their major axis perpendicular to each other and then rotate one element to align the major axis.

The strap concept would be extremely complex and hazardous to incorporate. Stationkeeping at the close proximity required would be undesirable. The concept is limited to an automated design. Standoff or pads are required between modules. The tension or pressure applied by the clamp will be critical in certain assemblies (e.g., propellant tanks).

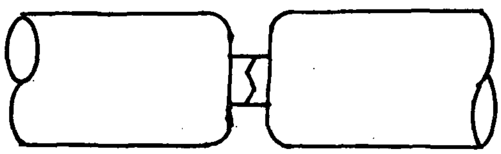
Permanent Connection



The permanent connection concept is equivalent to a "field splice" or on orbit welding of elements together. Obviously this concept is not acceptable for transport or temporary assembly cases. Operational assemblies such as the MSS, OPS or RNS could use this concept. It could be accomplished by either a manual approach or by an automatic concept. The primary undesirable operational characteristic is that it all but precludes modular disassembly, repair and/or replacement.

Mating Port Connection Only

"PREFERRED"



Reliance upon the mating port design concept to provide post capture rigidization would be the preferred technique. One set of equipment for both mating and orbital assembly functions would provide maximum commonality. Programmatic costs could also be minimized provided the requirements of both activities can be met without undue complexity in the equipment. Therefore, the preferred design concept is use of the mating port for post capture rigidization.

The approach used to establish the applicability of the mating port for rigidization is to identify the potential loads that will occur at assembly interfaces and determine if the mating port is or can readily be made compatible with these loads.

A docking and structural interface assessment was conducted. The results of the analyses are contained in Appendix A8. Four docking concepts were evaluated: (1) square frame, (2) probe and drogue, (3) ring cone, and (4) international docking. Based upon the alignment attenuation, and pull down requirements for mating, it was determined that the axial loads associated with transport thrusts of the TUGS, CPS and RNS were within the capability of all four docking concepts. It was assumed that the thrust was through the combined center of mass of the vehicles. Supplemental ridization provisions were not required.

Utility Interconnect

Electrical interconnect options were briefly described in Mating. For maximum flexibility and minimum complexity, manual interconnects are preferred. However, some electrical interconnects are required where manual access to the operation is impractical (e.g., CPS stage to CPS stage).

Fluid interconnects are discussed in detail in Cargo Transfer (Volume II, Part 4, Section 2) and Propellant Transfer (Volume II, Part 4, Section 3). If the interface is accessible, a manual plumbed approach is preferred. That is, an interconnect between the elements/modules is manually made. The concept includes provisions for either shirtsleeve or IVA operations. Also, provisions are made for isolation of the interconnect from habitable environments during the fluid transfer and purge operations.

If access is not practical (e.g., propellant tank study), an automatic concept such as illustrated in Figure 2-13 can be implemented. This concept is essentially the same as currently used on the Apollo S-II. It is adaptable to any of the four docking concepts evaluated.

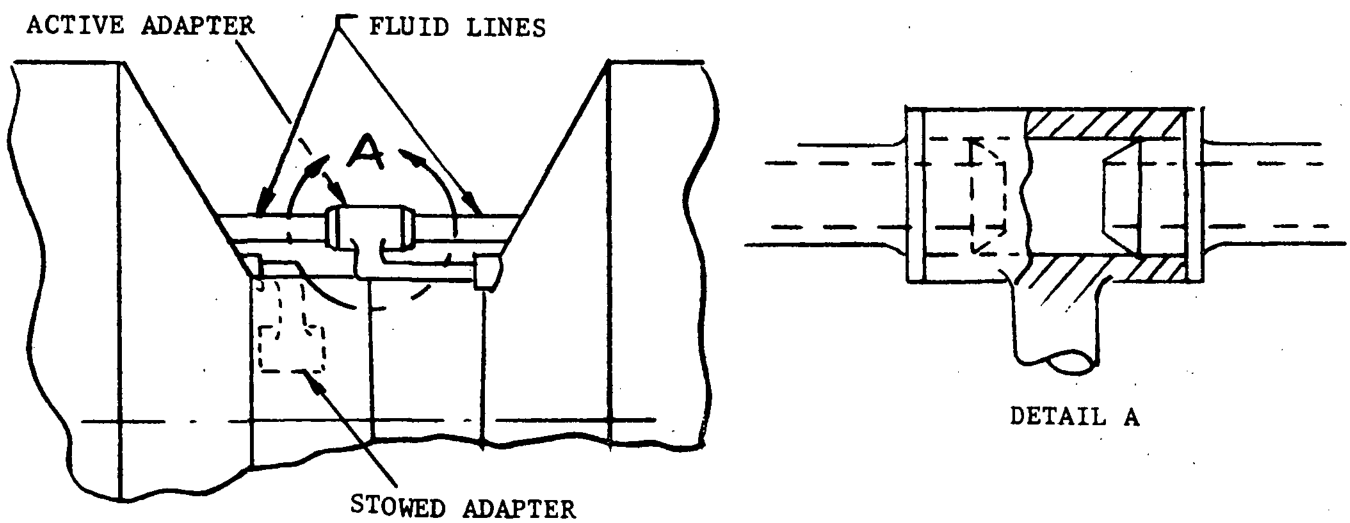


Figure 2-13. Probe/Drogue Fluid Line Connection

Operation:

Adapter on passive vehicle remains in stowed position. Adapter on active vehicle rotates and extends to operational position. Fluid lines containing probes extend and engage drogues in adapter.

PREFERRED APPROACH SELECTION

The alternates for post capture rigidization and utilities interconnect are automatic, manual shirtsleeve, and manual IVA. As noted previously, post capture rigidization is not required because mating port designs are such that they provide the necessary rigidization without supplemental hardware. Therefore, this section shall limit the discussion to connection of interfacing electrical and fluid lines. Table 2-3 is a list of various factors by which each of the alternates can be compared in an attempt to identify if any alternate is superior or generally inferior. The detailed rationale for each factor is contained in Volume II, Part 2, Section 2.0.

Table 2-3. Alternate Comparison

Comparison Factor	Alternatives		
	Shirtsleeve	IVA	Automatic
Technology	Preferred state of the art	Acceptable - some development req'd	Acceptable - some development req'd
Checkout/ Maintenance	Preferred	Acceptable - for checkout, less acceptable for maintenance	Acceptable - for checkout, not acceptable for maintenance
Relative cost	Low	Low-medium	High
Commonality	Least preferred	Preferred - common with shirtsleeve	Least preferred
Safety	Acceptable	Least preferred	Acceptable
Frequency of Activity	Preferred	Acceptable - if other IVA activities are required	Acceptable
Reliability	Preferred	Acceptable	Acceptable
Near Term Bias	Preferred	Acceptable	Least preferred
Far Term Bias	Preferred	Acceptable	Acceptable

Post Mating Activities Selection

Post mating operations are closely related to crew and cargo transfer and attached element operation activities. An integrated preference is for shirtsleeve operations wherever possible. Structural rigidization via the direct docking system is adequate in all cases. Utility interconnects are required on the MSS, OPD, CPS, RNS, and some tug payloads. CPS, RNS, tug interconnects are all recommended to be accomplished automatically. The number of interconnects is quite limited in all cases because the payloads are either dormant or operating in conjunction with a separate control center. MSS and OPD (manned) interconnects can readily be accomplished in a shirt-sleeve manual mode. The complexity of automated interconnects for these latter two elements is not warranted.

Pre-Mating Activities Selection

Both permanent (MSS, CPS, RNS, OPD) and temporary assemblages (MSS and lunar payloads on the CPS/RNS) were examined for initial mating operations. Either the direct dock or the manipulator concept could be utilized in these assembly operations. A manipulator is highly desirable for MSS assembly primarily because of the potential margin of safety that can be achieved by the more direct control and potential automation of the placement of modules after the initial mating of the EOS and MSS. Direct dock was preferred for assembly of the CPS, RNS, and the payloads on these two transport elements primarily because the required reach of the manipulator if used would exceed 100 feet.

Single module exchange or interchange did not show a strong preference for either of the two concepts. The final recommendation was a combination of the direct dock and the manipulator approach. Multi-module temporary assembly did illustrate a preference for the direct dock concept. This activity as in other activities such as mating, separation, EOS payload deployment, and EOS payload retraction favored the direct dock concept for almost all on-orbit operations. However, the manipulator was either required or highly desirable for various unique operations. It was pointed out that either concept could be adapted to the tasks required but in certain cases the penalties would be large and the designs extremely complex and costly. Therefore, the integrated preferred approach is a combination pivotal direct dock and manipulator. Based solely upon frequency of applicable operations, the direct dock is preferred as the baseline.

Rigidization of multi-module assembly on transport vehicles was evaluated in conjunction with attached element transport considerations. Many cislunar payloads (LSB, resupply modules) must be delivered in a disassembled or stacked configuration. A special multi-docking adapter is required for assembly of the lunar payloads. The design of the adapter must be compatible with delivery to earth orbit by the EOS. This limits considerably the number of viable options for design. A design concept model (Figure 2-14) was defined in conjunction with attached element transport analyses. It consists essentially of three "beams" each with three in-line docking ports. The beams are sequentially assembled at 60 degree angles. Note that the outboard docking ports pivot to minimize the assembly alignment problems.

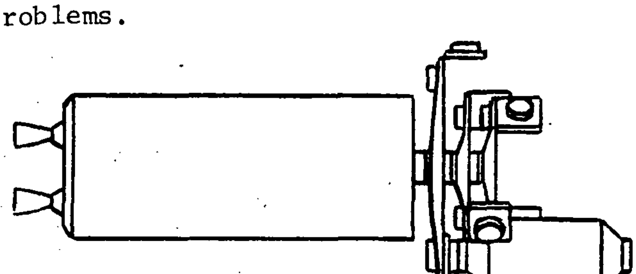


Figure 2-14. Cislunar Shuttle Payload Adapter

DESIGN INFLUENCES

Initial Mating Activities

If the manipulator concept is selected, then the various candidate assembly elements will be designed with mating ports and will be equipped with manipulator end effector receptacles. The EOS orbiter and the manned space-based tug are the only elements that are recommended for inclusion of a manipulator.

If the direct dock concept is selected, the various candidate elements will be equipped with direct docking ports. Laser radar transceivers will be required at the module assembly interface and passive radar reflectors on the other element. An option is to locate the laser radar transceiver in the EOS orbiter and space-based tug such that viewing will be up the side of the modules. Passive reflectors would then be located on the mating element such that the radar transceiver could detect them and, using triangulation methods, determine alignment at the docking ports.

Multiple docking adapters or rigidizing hardware will be required to support temporary matings of assembly complexs on cislunar shuttles.

Post-Mating Activities

Shirtsleeve connection designs should be implemented for all permanent element assemblies except the CPS, RNS, and OPD. The CPS, RNS, and OPD elements require automatic techniques for interconnecting the modules. The OPD may be such that intermodule travel can be performed. If this is so, then IVA or shirtsleeve interconnects are acceptable.

Temporary assemblies which will have shirtsleeve interconnects are those involving the MSS DRAM and earth orbital resupply modules. Geosynchronous MSS and OLS which interface with the CPS and RNS for boost to higher energy orbits could have utility hookup requirements, although they will be small (one or two connectors). This interface can be made automatic. The only interface that is definitely an automatic interface is that which involves an unmanned space-based tug and a temporarily attached payload. The necessity for providing a utility interface between the unmanned space-based tug and the payload is questionable. The one exception is during the propellant transfer operation involving the refueling of the tug. This interconnection must be automated for both electrical and fluid interchanges.

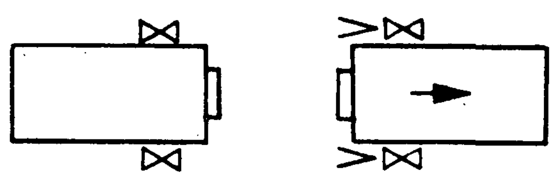
2.3 SEPARATION

The separation activity for this study is applicable only to elements that interface at a mating port. The activity includes prerelease events (disconnect of electrical and fluid interfaces, checkout of separation systems, hatch sealing, etc.), release (physical uncoupling of the elements from the mating port), and separation maneuvers required to provide clearance between the vehicles such that the elements can perform independent operations.

ALTERNATE APPROACHES

Four alternate approaches were visualized for separation: (1) jet translation which utilizes jet thrusting to separate the mated elements, (2) mechanically imparted thrust which utilizes some mechanism that can store energy in a mechanical form and release it upon command to impart a separation thrust between the elements, (3) combination (mechanically imparted thrust and jet translation), and (4) mechanical extension (manipulator) which physically separates the elements utilizing some type of extension arm.

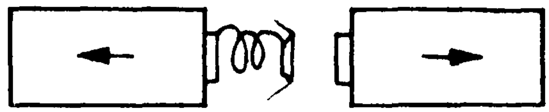
Jet Translation



The jet translation approach can employ two methods. It can be performed utilizing jets on one of the two elements to achieve separation, or both elements can simultaneously utilize their jets to achieve separation. The criteria for the selection of the latter is the need to separate rapidly without imparting excessive g-levels on either element.

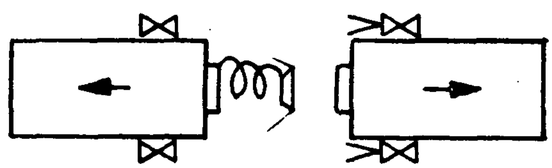
This jet translation separation method is dependent upon the propellant being available for the separation task and that vehicle propulsion jets be so located that they are capable of providing a linear translation along the mating port centerline. Because it is highly unlikely that all satellite configurations will be known in the near future, it is necessary for the delivery elements to be designed to provide the translation thrust to accomplish separation. Another problem with jet translation is that jet exhaust plumes may impinge the separating elements and damage or contaminant them such that their operational capability is affected. Therefore it is not only necessary to provide correct jet location, but plume shape and types of propellants may also have to be controlled.

Mechanically Imparted Thrust



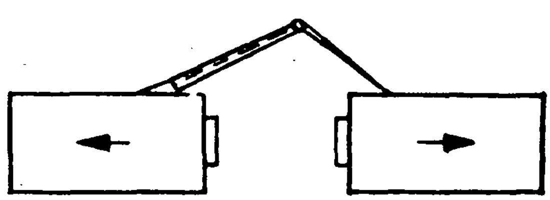
This approach employs the use of a mechanism (e.g., spring, pneumatic or hydraulic piston, tension ties, etc.) that can impart translational motion between the mated elements to achieve separation. The array of elements that a single element can mate with requires that the thrust applied by the mechanism be controllable (i.e., forces applied to separate two 100,000-pound masses would not be the same as that required to separate a 100,000-pound mass from a 100-pound mass). Also, this method does not allow one element to remain in a fixed position without resorting to the use of reaction jets to counteract applied forces. If the thrusting element does not apply the force directly through the center-of-mass of the element, a torque will be applied that must be counteracted in order to maintain a fixed attitude and direction of flight.

Combination (Mechanically Imparted Thrust/Jet Translation)

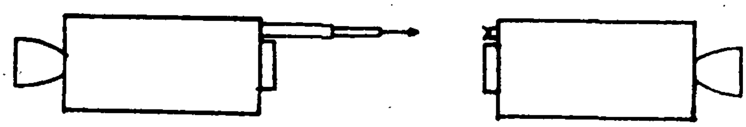


This approach utilizes both of the preceding options to achieve separation. It first applies a mechanical thrust to achieve initial separation, then one or both of the elements use jet translation to complete the separation activity. The advantages of this method is that the initial thrust can be low level. Also, if the initial separation is great enough, jet plume impingement can possibly be reduced to an acceptable level.

Mechanical Extension



The mechanical extension approach uses a device that physically separates attached elements to a relatively safe distance prior to any individual control. The illustration depicts a manipulator concept, however, several other techniques are equally as functional, particularly if the device is utilized solely for separation operations. The extension-retraction probe, illustrated below, is one such device that appears to have some validity and is one of the mating alternates.



Extension - Retraction Probe

With the manipulator separation method, if a manipulator is not attached to one of the separating elements, a third element containing a manipulator must be available for use. Manipulator operations do provide the capability to achieve controlled separation and can strategically place a separated element in a stabilized attitude.

The extension-retraction probe is essentially a manipulator with a single degree of freedom. The probe(s) must be located such that it will apply translational forces along the mating port longitudinal axis. The probe(s) must maintain alignment and attitude stabilization of the element being separated relative to the element the probe(s) is permanently affixed to. The handicap associated with the use of such probes is that if they must provide wide separation between elements, it would be difficult to maintain the required strength and stiffness and still be able to stow the probes when the are retracted and not interfere with mating port passages.

Two of the alternatives were eliminated from the study. The "mechanically imparted thrust" was eliminated because it would not be universally acceptable. The numerous element pairs that must be separated are of such vastly different characteristics (configuration/mass) that multiple independent designs would be required. The "combination" concept utilizes a mechanical thruster which imparts less thrust than the foregoing concept and could possibly be made universal. However, it still could not apply a translational force through the c.g. of many of the element pairs. Without this capability, the separating elements would be rotated at time of separation requiring that an ACS be available immediately to counteract this rotation. This eliminates one of the major benefits of the mechanical thruster; reduction in plume impingement.

The remaining two concepts illustrated by Figure 2-15 were the preferred approaches for which in-depth analyses was conducted.

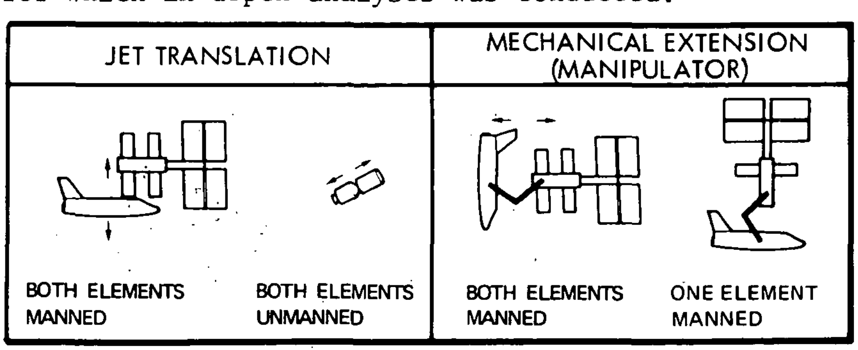


Figure 2-15. Preferred Separation Approaches

DESIGN CONCEPT MODELS

Applicability of the separation concepts to the array of study elements required that a series of hardware design models be selected or developed for each separation function. The model was considered valid when it was compatible with the procedures, requirements, and study element designs.

Manipulator Model

Figure 2-4 in Mating depicts the manipulator design to be used for the study model where the manipulator separation concept is applicable. The manipulator can be directly controlled manually, it can be computer controlled, or it can be remotely controlled. The assembly consists of upper and lower structural elements, pivot joint actuators, and the wrist mechanism. The arm carries a remote control TV camera and spotlight mounted near the terminal end of the arm. Dual torque motors are provided and designed such that failure of one motor does not prevent drive by the other. The no-load slew speed at the terminal end of the wrist ranges between 0.05 and 1.5 feet/second.

A manipulator can separate an element either by directly translating it from the mating port or by translating and rotating the element. Figure 2-18 illustrates these two options. The direct translation results in the minimum separation distance because of the manipulator geometry and end effecter location. The direct translation however, will be required where appendages interfere with an element when rotation is applied. The direct translation of a modular space station with the end effector receptacle located at the midpoint of the station (similar to Figure 2-16) allows a maximum separation of about 10 to 13 feet with a berthing port forward of an EOS Orbiter crew compartment and a maximum separation distance of about 15 feet with the berthing port behind the crew compartment. If the end effector receptacle location can be placed at a point on the modular space station closest to the manipulator base when berthed, the maximum separation distance can be increased to near the maximum length of the arm, however, this could be the worst location for manipulator control of the element.

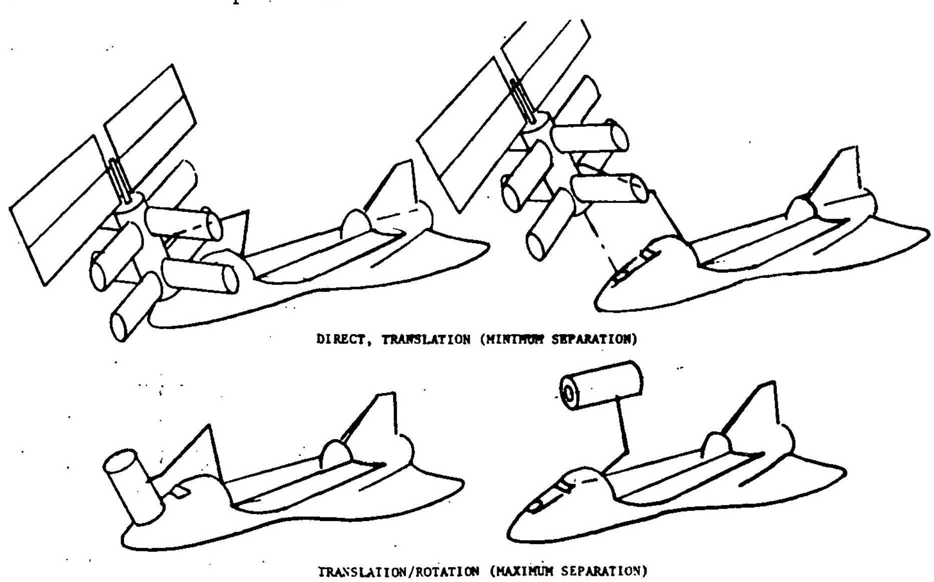


Figure 2-16. Manipulator Separation Concepts

Alignment Model

The alignment criteria for the separation activity is in general not critical except where contact with appendages are possible such as when separating a module from a modular space station. Two alignment concepts are available for use, laser radar and visual observation. The laser radar concept is actually not viable until the separation distance is such that the laser targets can be acquired (greater than 3.5 feet for a 2 foot diameter target pattern). Not only does the approach have to acquire the target, it must recognize and respond to this recognition. If the vehicle misaligns before acquiring the target pattern a greater separation will occur before acquisition is accomplished. It may be that mating can accept the loss of acquisition at some minimum distance due to a mate commitment (point of no return). However, for separation, if appendage clearance is critical, then some type aid must be available to maintain alignment at start of separation. If the separation rate is low enough, visual observation is acceptable for manned elements, however, with a rapid separation rate, reaction time may not be satisfactory and an automatic system that interfaces directly with the control system is required.

Because alignment is necessary when separating two unmanned elements and because a laser radar alignment concept is selected for mating, this concept should also be the model for jet translation separation. Figure 2-17 is a block diagram of a scanning laser radar concept that is applicable for both mating and separation.

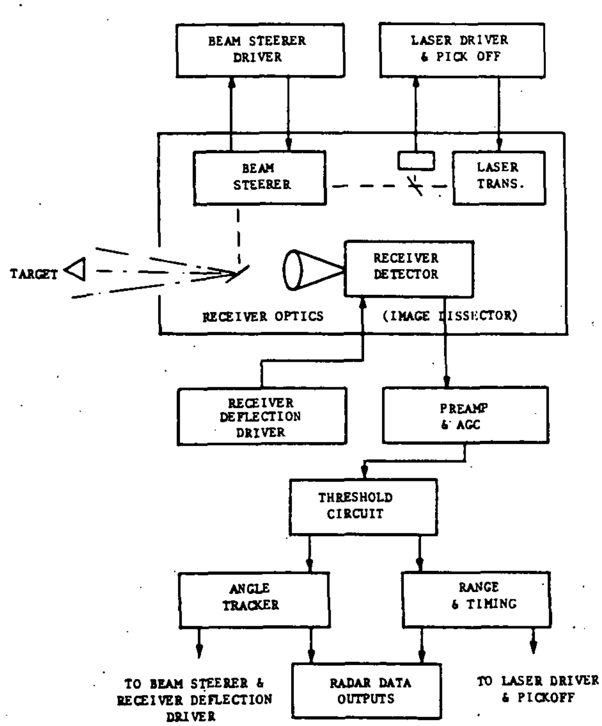


Figure 2-17. Scanning Laser Radar Basic Block Diagram

FUNCTIONAL REQUIREMENTS

The requirements are essentially developed around four categories: (1) active operations which includes alignment criteria, separation distances, and mating port and manipulator dynamics, (2) monitoring and sensing activities which includes requirements for systems verification, separation sensing, alignment knowledge, and communications, (3) pre-separation activities such as tunnel depressurization, interface disconnecting, and alignment of inertial measurement systems, and (4) general criteria such as jet plume impingement control, backup criteria, and illumination. Where applicable, the requirements have been quantified.

The two functional requirements that most strongly influence the preferred approach selection are (1) alignment during separation, and (2) contamination (plume impingement) of one of the separating elements.

PREFERRED APPROACH SELECTION

Two approaches to separation have been considered: jet translation and manipulator extension. Both concepts can be performed manually or automatically and both offer significant advantages. The jet translation offers low cost simplicity because at least one of the separating elements for all pairs will be equipped with an RCS that could be used for the separation task. The manipulator offers a more safe approach in that the elements can be physically separated some distance before independent operations commence. Table 2-4 compares these and additional factors to determine if there are any significant advantages or disadvantages for using one approach as opposed to the other.

Table 2-4. Separation Approach Comparison

FACTORS	ALTERNATES			
	JET TRANSLATION		MANIPULATOR	
	MANUAL	AUTOMATIC	MANUAL	AUTOMATIC
Technology	Preferred-state-of-the-art	Acceptable-technology available	Least preferred-	Least preferred-
C/O Maintenance	Preferred-least parts/complexity	Acceptable-adds alignment/range sensors	Not acceptable-except on elements that periodically return to ground	Not acceptable-except on elements that periodically return to ground
Safety	Least preferred	Least preferred	Preferred-provides a separation before independent operations commence	Preferred-provides a separation before independent operations commence
Reliability	Preferred-least parts	Acceptable-with redundant sensors	Least preferred-Multiple parts	Least preferred-multiple parts
Commonality	Acceptable-still requires automatic jet translation	Preferred-commonality across all element pairs	Least preferred	Least preferred
Relative Cost	Least cost	Low cost	High cost	High cost
Plume Impingement	High	High	Low	Low
Near Term Bias	Preferred	Acceptable	Least Preferred	Least Preferred
Far Term Bias	Preferred	Acceptable	Least Preferred	Least Preferred

The detail rationale for each of the evaluation factors is contained in Volume II, Part 2, Section 3.0.

Synergistic Preference

The next step is to look at the other activities in the orbital operations study and determine if the selection of a jet translation concept affects their conclusions or their preferences perturbate the separation selection. Those activities that are affected by the approach selection are Mating, Orbital Assembly, Payload Deployment, and Payload Retraction. These interactions and preferences are developed and analyzed in Appendix A5 and summarized in paragraph 2.5 of this report.

As indicated by the trade study, there are some preferences for a manipulator design, but in general the evidence indicates that jet translation is acceptable. Therefore, the separation activity continues to prefer the jet translation concept. If the commonality studies result in a manipulator selection, the separation designs will not be perturbated. The results of such a selection should on the other hand enhance operations by providing the additional safety provisions and reducing plume impingement problems.

Approach Selection by Element Pairs

Separation between single module elements presents no unique problems. The operations can be closely akin to the Apollo program. Separations from the EOS must account for the appendages (wings, tail) of the EOS but all concepts currently envisioned provide adequate clearances for the separation maneuver.

Separation from the MSS are more critical. Precise alignment must be maintained because of the proximity of adjacent modules. This alignment is actually more critical for separation than mating. The most critical time is at the minimum separation distance. At mating the alignment can reach the limit because the docking port is designed to accommodate misalignments. When separating a corrective "maneuver" is required if the alignment limit is approached.

Two MSS adjacent module separation operations occur relatively frequently. They are (1) departure of free-flying RAM's, and (2) rotation of resupply modules. The preferred approach for these operations is the manipulator because of its increased margin of safety in having a more direct control of the operation and its potential for total automation.

Jet translation concepts were evaluated to determine their adequacy for separation operations in conjunction with the MSS. Inclusion of a laser scanning radar on the MSS and passive laser reflectors in a prescribed pattern can provide the necessary accuracies and control data for the operation. (The laser and reflector have been identified as required or at least highly desired in several other interfacing activity analyses.)

Contamination of sensors on the MSS, RAM and/or satellite is of definite concern during all thrusting maneuvers. The separation activity is a potential problem area because of the close proximity of the elements. Tugs, the MSS, and the EOS must interface with RAM's and satellites. Because the RAM and satellites transport tugs can be unmanned, a manipulator concept is not feasible for separation. Also during the transport and stationkeeping operations tug attitude control systems will be expelling contaminants. Therefore, both RAM's and satellites must be configured to protect contamination prone sensors either by selected sensor placement or by deploying shields.

Similarly sensors on the MSS must also be protected. Close proximity stationkeeping operations with other free-flying elements will expose the MSS to contamination. Examination of plume impingment geometry indicates that regardless of the approach, the free-flying elements are more susceptible to contamination at separation distances of 50 to 60 feet than at lesser ranges. Therefore, the concept of the manipulator does not circumvent the contamination problem. Similar geometric relationships exist for the EOS.

At least one of the elements involved in every separation activity has translation capability. If the alignment problem associated with MSS-element separation can be resolved, a manipulator cannot be justified for separation purposes. The preferred approach for all separation activities is jet translation.

DESIGN INFLUENCES

Table 2-5 identifies the preferred hardware for each noted element based on the preferred conceptual approaches for separating the various element pairs. The following paragraphs are a synopsis of why each piece of hardware was allocated to the noted elements.

Table 2-5. Separation Hardware Preference

HARDWARE	ELEMENT													
	EOS	RTN Tug	Space Based Tug	EOS DRAM	MSS ARAM	MSS DRAM	SAT	EO Resup Mod	MSS	CPS OIS	CPS CLS	RNS	OLS	OPD
Separation Extension Device	X	-	-	-	-	-	-	-	-	-	-	-	-	-
Extension Device Recept	-	-	-	X	-	X	X	-	-	-	-	-	-	-
Jet Translation Capability	X	X	X	-	-	Note 1	-	-	-	X	X	X	-	-
Laser Radar XCVR	-	-	X	-	-	-	-	-	X	-	-	-	-	-
Passive Laser Radar Reflect	-	-	X	-	X	X	-	X	X	-	-	-	X	-
TV Camera (Note 2)	-	X	X	-	-	-	-	-	-	X	X	X	-	-
Direct Visual Align Scope	X	-	-	-	-	-	-	-	-	-	-	-	-	-
Visual Alignment Targets	-	-	-	-	-	-	-	-	X	-	-	-	X	-

NOTE 1: The MSS-supported DRAM requires translation capability if it is to free-fly and direct-dock to the MSS.

NOTE 2: TV camera is an option to the laser radar and passive reflectors. TV coverage to a remote site will provide the same information at lesser accuracy than radar alignment sensors, but vehicle control can be directly integrated with the laser radar concept and not with TV.

Separation Extension Devices

This device can be a manipulator or some other design that can be used to separate elements that are susceptible to contamination through plume impingement. Because the device will not be required for all separation activities, it should be removable from the EOS orbiter in between required missions.

Extension Device Receptacle

This is the matching receptacle for the above noted device. It is allocated to those elements that are most probable to be plume impingement sensitive.

Jet Translation Capability

This capability is allocated to the logistics vehicles. Each of these elements perform jet translation separations from multiple elements. The single exception is the MSS supported DRAM which may be required to free-fly between the MSS and its operational orbit. For such a case, the DRAM will perform the translational separation with the MSS providing backup assistance, if required.

Laser Radar Transceiver

As noted, the only time alignment maintenance during separation is critical is when a module is separated from between other modules of an MSS or OLS. Because manned logistics elements can successfully perform a separation using a direct visual alignment aids, where man is available, as in the case of an EOS orbiter, this will be the mode. For elements that may or may not include a man, such as the space based tug, the laser radar concept is recommended. The MSS is provided a laser radar as a backup tool for the critical separations and for guiding a free-flying DRAM during its separation. The OLS is not equipped with a transceiver because it will be unmanned during most of its low earth orbital assembly operations. It may be that its operations in lunar orbit will include the requirements; however, it is not necessary for low earth orbital operations.

Passive Laser Radar Reflectors

The radar reflectors are installed on elements that will be separating from an element that is equipped with a laser radar transceiver.

TV Camera

An option to the information provided by a laser radar system is a TV camera directly viewing the separation and transmitting the data to a remote control center. The accuracy of the information is much less, however, if general characteristics are acceptabe, the TV camera is the least cost. Because the unmanned logistics elements (return tug, space based tug, CPS, and RNS) all perform non-critical alignment separation, the TV camera will efficiently provide any necessary data.

Direct Visual Alignment Scope

This hardware is allocated to the EOS orbiter only because it is the single logistics element that is always manned and does not require the more expensive laser radar hardware to perform a jet translation separation.

Visual Alignment Targets

Visual alignment targets are required on the MSS and OLS only. These are the elements which the EOS orbiter separates from and can involve a relatively critical alignment during the separation.

2.4 EOS PAYLOAD DEPLOYMENT/RETRACTION AND STOWAGE

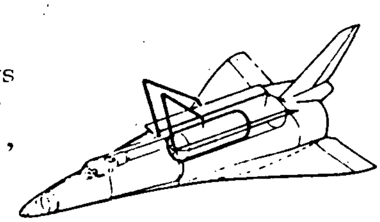
These two interfacing activities are so interrelated that they can best be summarized in a combined presentation. EOS payload deployment is defined as the operations involved in releasing the payload from the retention system in the cargo bay, extending the payload beyond the EOS moldline, and, as required, readying the payload for separation and/or operations. Retraction and stowage of EOS payloads is the converse or reverse set of operations.

ALTERNATE APPROACHES

There were five alternate approaches studied as possible candidates for deployment/retraction and stowage of a payload. The approaches are:

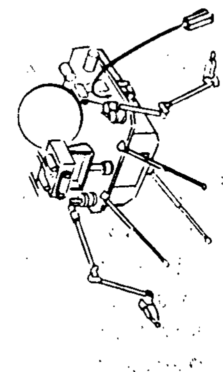
1. Manipulator
2. Teleoperator
3. EVA and AMU
4. Lateral Translation
5. Pivot Mechanism

Manipulator



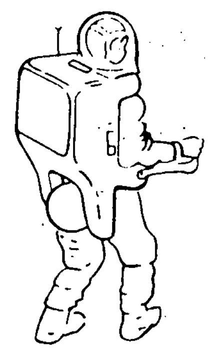
The manipulator is an articulating boom with multiple degrees of freedom provided by joints, elbows and pivots. The manipulator approach has three major assemblies: (1) a support platform - the EOS orbiter, (2) articulated arms - 2, and (3) tools. Power, command, and control must be provided by the orbiter for each assembly. The support platform maneuvers the arm assemblies into a position to perform the desired deployment functions. The manipulator arms produce the tool positioning motions and forces. They characteristically have multiple degrees of freedom; from three in simple systems to as many as eight in complex sophisticated installations. The control and skill requirements and mechanization complexity increases proportionally to the number of degrees of freedom.

Teleoperator



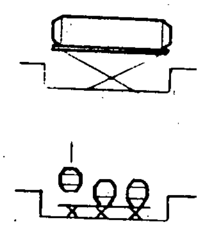
The teleoperator approach is a system level concept and would be a separate spacecraft in element inventory. The teleoperator spacecraft illustrated in the figure consists of a structure housing the spacecraft systems, a propellant supply tank, four sets of quad thrusters, a two axis camera mount, binocular TV cameras and lights, a single close-up TV camera, two manipulator arms with interchangeable end effectors, and three docking arms. Control of the teleoperator will be accomplished from a control station within the orbiter.

EVA and AMU



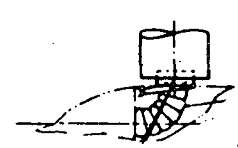
The use of EVA and a orbiter crewman in an Astronaut Maneuvering Unit (AMU) is the most restricted of the five approaches. It utilizes, as illustrated in the figure a suited crewman with a backpack. The backpack contains the crewman's life support, propulsion, attitude control electrical power and communications/data. Attached to the backpack is the oxygen storage bottle. The front of the unit has two hand controllers, one for translation, the other for attitude hold. The hand controllers rotate down when not in use.

Lateral Translation



The lateral translation approach provides a carriage assembly mounted on rails, screw jacks, etc., that laterally extend the payload beyond the moldline of the orbiter.

Pivot Mechanism



The pivot mechanism is a rotational approach that pivots the payload 90 degrees with respect to the orbiter centerline. The pivot point can be located at either the forward or aft bulkhead of the cargo bay. There are options for flexible tunnels that can be added to the pivot mechanism to provide shirtsleeve crew passage to the payload in either the stowed or deployed positions.

The five candidate approaches were reviewed and the following factors were used to select two approaches for further study:

Approaches Eliminated	Rationale
(1) Teleoperator	Because numerous Orbiter missions do not involve an element already on orbit, the teleoperator would have to "deploy" itself and therefore it reduces the effective cargo bay volume. It also adds another element to the vehicle inventory requiring an additional development program. It also has no significant advantages over an EOS manipulator approach.
(2) EVA with AMU	The EVA with AMU was rejected because of its potential hazardous operations. It was also severely limited in the size of payloads that could be handled It also has the further disadvantage of being a new development.
(3) Lateral translation	The lateral translation approach has been eliminated from further study consideration because all of the functional requirements, operational procedures and alternates associated with lateral translation devices do not vary sufficiently from the pivot mechanism to offer any significant advantage to studying this alternative.

Therefore the approaches that were selected for further study and analysis were: (1) pivot mechanism and (2) manipulator. The data in the remaining sections were established utilizing these two preferred approached illustrated by Figure 2-18.

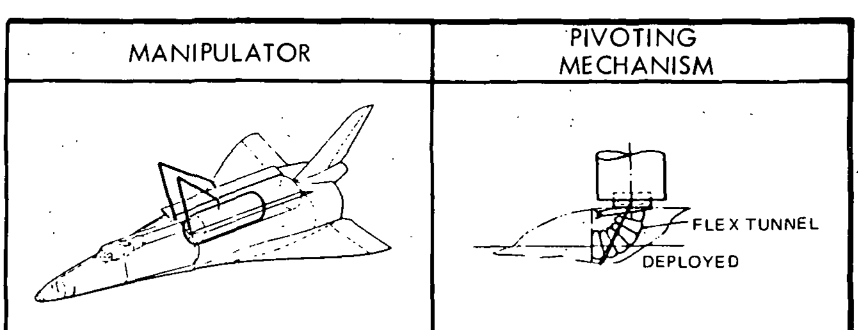


Figure 2-18. Preferred Approaches

DESIGN CONCEPT MODELS

To be able to analyze the approaches that were developed specific hardware concepts were synthesized. They were used to evaluate the approaches and the viability of any hardware designs. In the interfacing activity of EOS payload deployment the EOS will be involved in 23 element-to-element interactions with the 24 elements of the space vehicle inventory. It is because of this principal involvement of the EOS that design concept models had to be defined for some of the major EOS/payload interfaces. The following are the models of EOS payload handling and servicing equipment that were utilized in the selection of a preferred element pair approach.

Payload Envelope

Figure 2-19 shows the dimensions of the orbiter payload bay. Within this bay the payloads are accommodated. A 60-foot module would have 27 inches total clearance for its length and if it were 15-feet in diameter it would have a 3-inch clearance at the bottom of the bay and 5-inches on each side of the bay.

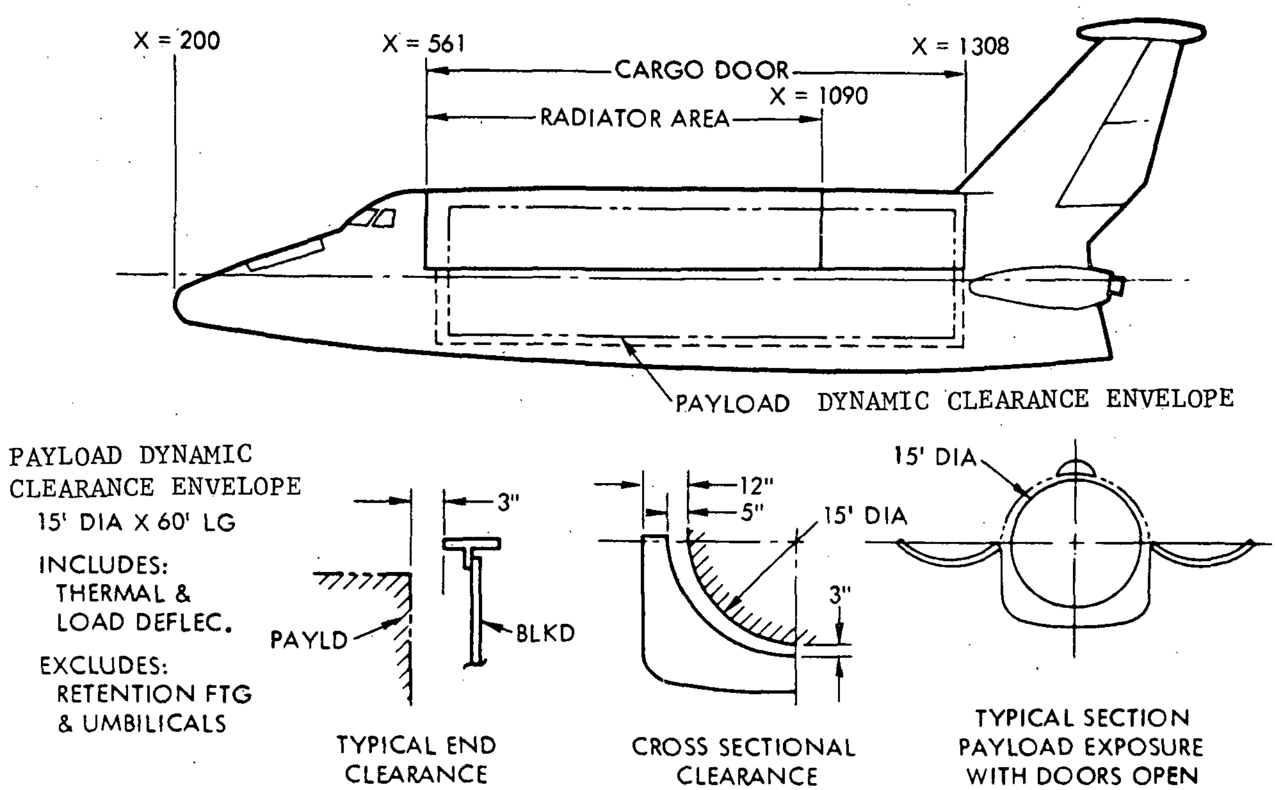


Figure 2-19. Orbiter/Payload Envelope

Manipulator

The EOS manipulator approach (Figure 2-20) consists of two manipulator arms, a manipulator operator station, a payload retention assembly and IVA tunnel connecting the payload bay and the crew compartment. In their stowed position the arms are above the payload. Each arm is 600 inches long (from shoulder joint to tip of end effector), with a maximum diameter of 15 inches.

Although the manipulator concept has with two arms, each arm is sized to accomplish the functional requirements. Manipulators generally have three major assemblies: (1) a support platform (EOS orbiter), articulated arms (2) and tools. Power, command, and control capability are supplied by the orbiter.

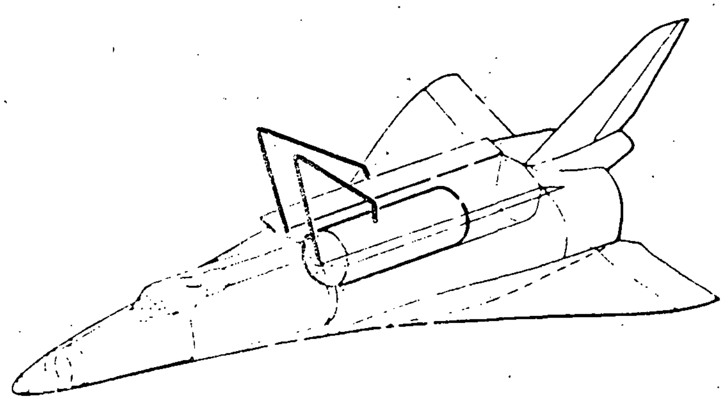


Figure 2-20. Manipulator/Payload Handling

Each arm has a shoulder, elbow, and wrist joint with two-degrees of rotational freedom at the shoulder, one degree of rotational freedom at the elbow, and three degrees at the wrist. The entire arm is capable of being jettisoned to allow closure of the cargo bay doors. Each joint is driven by redundant motors and is torque limited to prevent damage to the manipulator arm.

Each arm is sized to individually deploy a 65,000-pound payload (15 feet in diameter by 60 feet) a distance of 600 inches vertically out of the cargo bay, and rotate it 90 degrees. This operation is completed in a maximum of 5.2 minutes (Figure 2-21). Docking to another shuttle requires approximately 15 minutes from initial contact of end effector to positioning of the shuttles within 6 inches of one another to actual mating.

DEPLOYMENT TIME (MINUTES)

CENTER OF GRAVITY	PAYLOAD WEIGHT			
	65K LBS.	45K LBS.	25K LBS.	10K LBS.
A	5.2	4.3	3.2	2.5
B	7.0	5.8	4.3	3.4
C	9.7	8.0	6.0	5.0

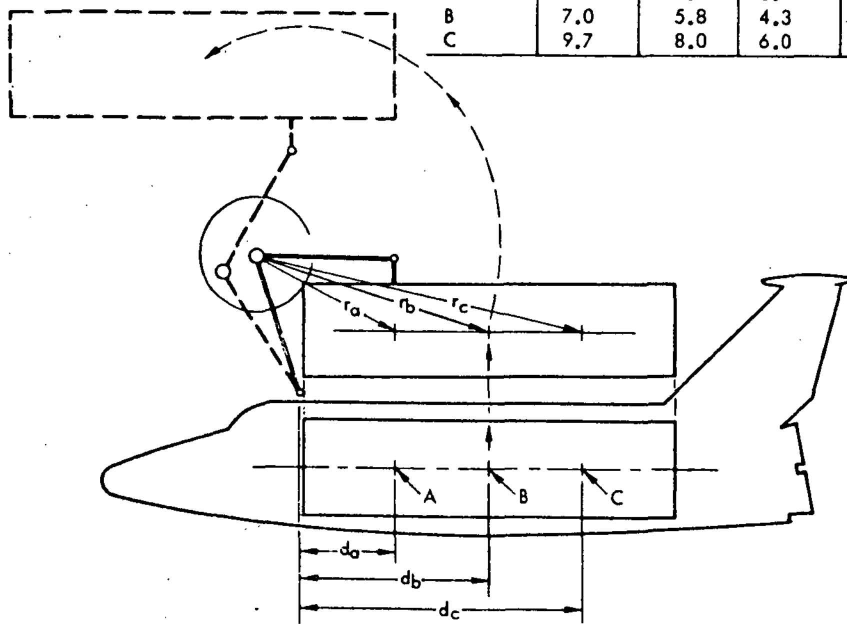


Figure 2-21. Manipulator Deployment Rates

Retention Concepts

There are a wide variety of possible payload retention assemblies. The payload retention assembly accommodates payloads 15 feet in diameter by a length that can vary from payload to payload. Payloads that are smaller in diameter than 15 feet will be retained by standardized pallets. Retention includes payload center-of-gravity (c.g.) control, as required by aerodynamic entry. Of the many potential candidates that exist each is characterized by the number of retention (attach points), their location (side wall or bottom of the cargo bay) and whether each attach point utilizes latches or simply reacts loads in a slot or channel. Figure 2-22 describes the type defined by MSS and OOS studies and a three point concept that was under study for possible orbiter use. The figure also shows two options for the attach point at the bottom of the payload and for two possible EOS/payload latching interfaces.

There are some large payloads that because of their particular design requirements cannot easily accept penetrations through the structure, and as a result must utilize a large clamp of a cylinder hinge and rotating mechanisms. While these payloads will not represent the majority of EOS payloads, they will be involved in a significant number of missions. Several of the tug concepts have experienced a need to utilize the large clamp or hinge approach. The applicability of these retention devices to the wide spectrum of payloads is obviously limited and a commonality analysis would eliminate them from consideration as a baseline concept.

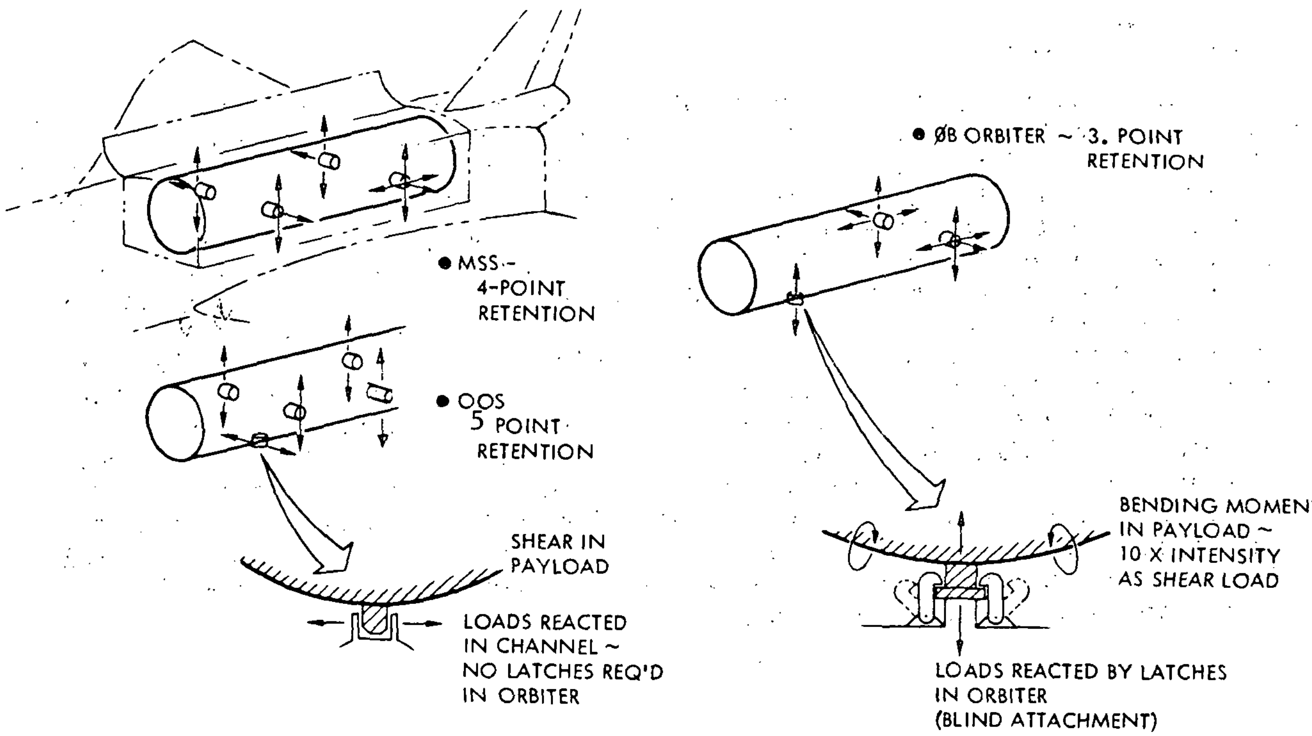


Figure 2-22. Payload Retention Concepts

Figure 2-23 shows the selected retention concept. The advantages of this selected concept are: (a) it employs a simple latch design, (b) no orbiter loads are transmitted to the P/L, (c) the P/L is not affected by the flexibility of the orbiter, (d) the side load in the keel saves 500 pounds in orbiter structure, (e) the lower fitting is a passive mechanism (slot).

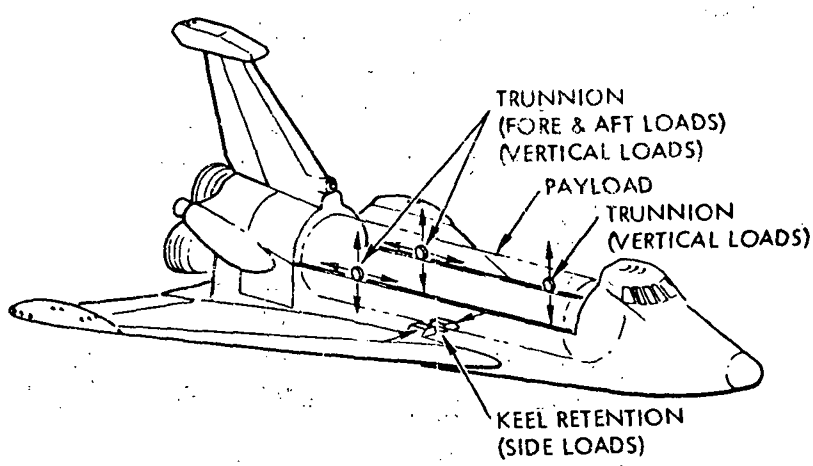


Figure 2-23. Selected Payload Retention Concept

Pivot Mechanism

This concept for the deploying of payloads is shown in Figure 2-24. The model used had redundant actuators and payload deployment drive mechanisms. It also contained a flexible passenger transfer tunnel. All deployment mechanisms have a manual override capability that the crew can actuate from the crew compartment. The actuators are located inside the airlock providing accessibility for in-orbit maintenance or emergency manual operation, (IVA). Torque shafts and adjustable push rod systems are routed through the airlock wall to latching and actuation points. All actuation have lock/unlock indicators and are inspectable by line-of-sight systems from the airlock aft viewing port. Crew transfer (shirtsleeve) is provided into the payload bay at the centerline by a flexible tunnel. This tunnel allows pressurized transfer into habitable payloads in either the stowed or deployed position. Hardware power, communications, and monitoring interface connectors, and other fluids/gases interfaces are located inside the connecting tunnel/hatch area (see item I, Docking Port and Hatch Locations) and are accessible (IVA) for payloads that provide a matching seal. Payload deployment is a simple 90-degree rotation out of the cargo bay.

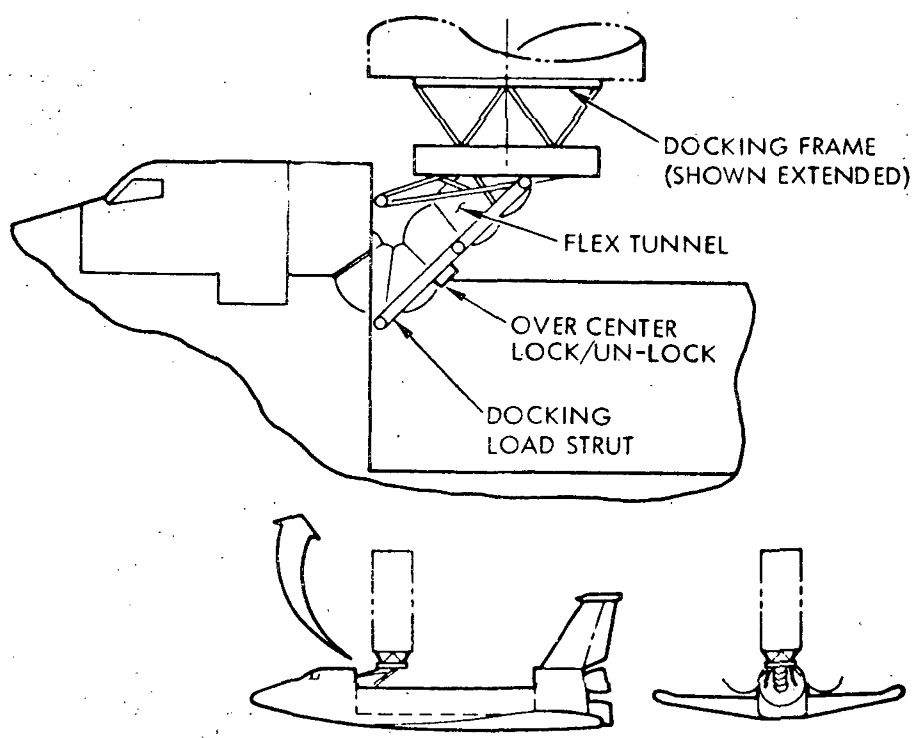


Figure 2-24. Pivot Mechanism Concept Model

FUNCTIONAL REQUIREMENTS

The functional requirements for the two approaches are essentially the same. Their accommodation of these requirements varies significantly. The manipulator is much more flexible in handling payloads in the cargo bay. But this flexibility is also of concern. Clearances in the bay are critical. A rigid concept such as the pivot mechanism provides a margin of safety during both deployment and retraction. Umbilical connects and disconnects must be automated with the manipulator. They could be made manually with the pivot concept (assumes forward bulkhead mounting and flexible tunnel).

Deployment and retraction of multiple payloads is impractical with the pivot mechanism unless the sequence is sequential deployment and then retraction. The manipulator concept has no such constraints. Crew access and continuous utility interconnect in the deployed mode can be readily achieved with the pivot concept. A berthing port and utility connect operation is required with the manipulator.

PREFERRED APPROACH SELECTION

Table 2-6 presents the results of a comparison performed between the pivot mechanism and manipulator approaches. The functional requirements and subjective evaluation factors were used for this comparison. The detail rationale for each rating can be found in Volume II, Part 2, Sections 4.0 and 5.0.

Table 2-6. Preferred Approach Comparison

Functional Requirement	Manipulator	Pivot Mechanism	Remarks
Handle payload in EOS bay	Excellent	Good	Flexibility of movement with manipulator
Disconnect umbilicals	Good	Good	Pivot mechanism can maintain continuous connection through erection
*Deploy multiple payloads	Good	Poor	
*Deployment rate	10 minutes	10 minutes	
Provide cargo bay illumination	Excellent	Good	Manipulator can move light source easily
Release attachments Separate payload	Mech. devices at end effector attachment	Mech. devices at mating interface	Manipulator can use second arm as backup
Provide utilities	Mult. service panels	Service panel on pivot	
Monitor payload status	Through ISS hardware	Through ISS hardware	
Maintain payload stability	Good	Excellent	
Place in proper orientation	Excellent	Good	Pivot mechanism utilizes EOS ACPS
*Extend payload from orbiter	Excellent up to 50 ft	Minimum distance	
Release payload	Best	Good	Distance allows for improved checkout and verification of deployment readiness
Provide manned entry to payload	Good (flex. tunnel kit)	Best	Pivot can provide manned entry in both deployed and stowed position
Evaluation Factor			
Technology	Slightly beyond the state of the art	State of the art	
Maintenance	Limited to EVA	Good	Some degree of maintenance can be designed into pivot mechanism
Operational complexity	Least	Slightly higher	
Reliability	Good	Best	
Commonality	Best	Poor	Pivot requires special adapters for many payloads
Relative cost	Slightly higher	Lowest	
Crew interface complexity	Highest	Lowest	Special training and high levels of crew involvement
Center-of-gravity control	Best	Poor	Attach point on pivot mechanism limited to ends of cargo bay

*Evaluated for intra-activity applicability

Based upon the analyses and evaluations selection of a singular approach for EOS payload deployment is not warranted. If only this interfacing activity were considered a preference for the pivotal concept is evidenced. It is less complex, lighter, less costly, and facilitates manned access to the payload. However, when consideration of the synergistic benefits that can be achieved by the use of the manipulator in assembly of the station, handling of multiple payload, and potential on orbit maintenance operations is included the manipulator is a highly desirable concept.

In addition to the added margin of safety inherent in the use of the manipulator for station module assembly operations (more positive control of modules in close proximity) the manipulator can be used for attaching modular packages such as an airlock laboratory or antenna package. Handling multiple payloads can be readily accomplished with the manipulator. The sequence of operations is not restricted and free flying close proximity operations can be avoided.

The principal advantages of the pivotal mechanism concept are:

1. It consists of a single system that can be readily used for single payload deployment and retrieval operations (adapter required for some satellites).

2. It provides a conventional and common on axis docking capability for mating with the orbiter or payloads with other elements.

3. It provides the potential for continuous shirtsleeve access to habitable payloads during cargo bay stowage and deployed payload operations without interruption of EOS-payload interface.

4. It provides the potential for shirtsleeve access (if necessary) to the deployment/retraction activities and the interface connections.

5. It provides a more positive control of the payload during erection and retraction operations.

Thus each approach has highly desirable features. Also each approach can be adapted to meet all the operational requirements identified. For example the pivotal mechanism concept could include a "rack" which would permit the handling of multiple payloads.

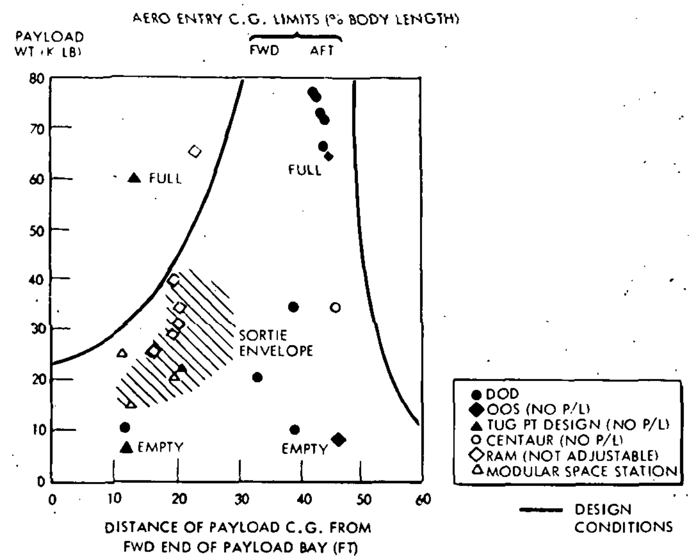
It is recommended that both the pivotal mechanism and the manipulator concept be developed. EOS programmatic considerations - cost, schedule, payload traffic models - rather than operational activities should determine the selection of the baseline concept. Development options include (1) selection of one as a baseline and kit installation of the other, 2) provisions for kit installation of both concepts, or 3) if the EOS traffic model permits, a sequential development of concepts on successive orbiters.

DESIGN INFLUENCES

The design influences for the EOS in the area of payload deployment, retraction and stowage are related to the decision that a pivot mechanism would be selected for use on the EOS orbiter to accomplish the primary functional requirements.

The design of the EOS payload retention concept was strongly influenced by the following factors.

1. Payload Longitudinal C.G. constraints



The above sketch depicts the physical limits on the travel that the payload can experience. The physics of this problem are influenced jointly by the design of the payload and the physical constraints of the orbiter.

2. Payload Retention Concepts

There are a wide variety of possible payload retention assemblies. The payload retention assembly accommodates payloads 15 feet in diameter by a length that can vary from payload to payload. Payloads that are smaller in diameter than 15 feet will be retained by standardized pallets. Retention includes payload center-of-gravity (c.g.) control, as required by aerodynamic entry. Of the many potential candidates that exist, each is characterized by the number of retention (attach points), their location (side wall or bottom of the cargo bay) and whether each attach point utilizes latches or simply reacts loads in a slot or channel.

The analysis of the various payload retention concepts established the trends depicted on the following Figure 2-25.

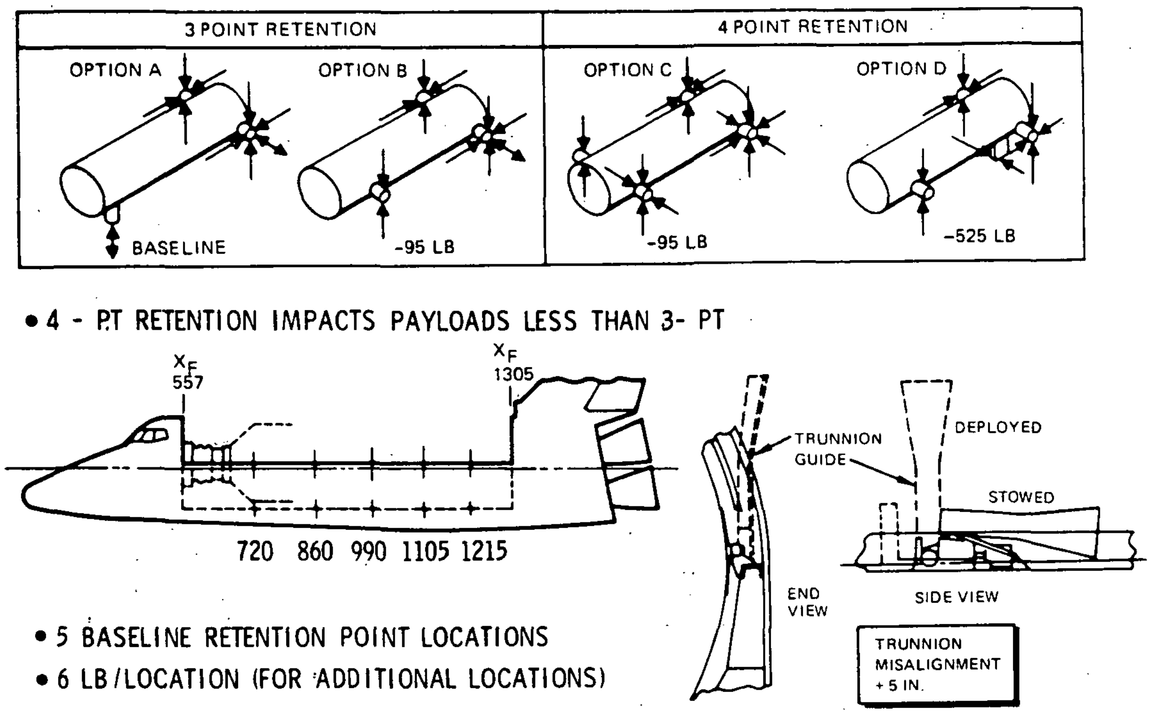


Figure 2-25. Payload Retention Concepts

Namely, (1) four-point systems were lighter than three-point systems, and (2) multiple retention point locations over the five baseline points are not a significant weight penalty (6 pounds/location).

The influence of multiple retention points on the weight of the payloads can be seen on Figure 2-26. The penalties are delta weight to the structure of the payload plus adapter to acception option D retention plus the reference 5 points. The delta is measured from the optimized reference concepts that were individually developed for each payload. Fifty percent of the penalties are attributable to the number of locations. This penalty would be eliminated by the selected concept of multiple retention points (24 inches to 48 inches O.C.). The other 50 percent is attributable to the retention method and can be minimized by the use of the recommended kits (see final conclusions).

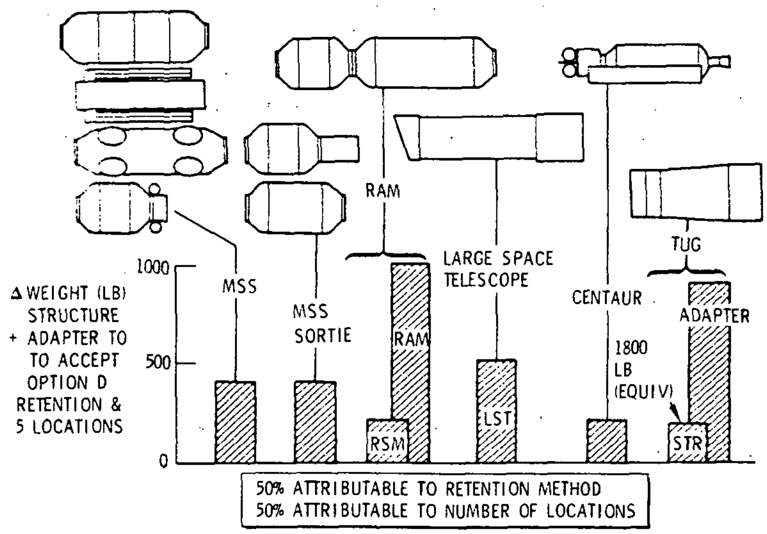


Figure 2-26. Payload Weight Penalties

This analysis, coupled with the c.g. location constraints, led to the following preferred concept for payload retention.

Figure 2-23 showed the selected retention concept. The advantages of this selected concept are:

1. It employs a simple latch design
2. No orbiter loads are transmitted to the payload
3. The payload is not affected by the flexibility of the orbiter
4. The side load in the keel saves 500 pounds in orbiter structure
5. The lower fitting is a passive mechanism (slot)

Thre are definite advantages to both the pivot mechanism approach and the manipulator. Although the pivot mechanism is the selected approach, there are two operations in which the manipulator has definite advantages. These two operations are:

1. Multiple payloads
2. Small satellites

If both deployment and retrieval of multiple payloads are required on the same mission, then a manipulator approach is favored. The use of one approach or the other is, therefore, dependent on the traffic model utilized. In the traffic model used for this study the frequency of multiple retentions or deployments was not high enough to make a manipulator the preferred choice. If at a later date in the EOS program the requirement to handle multiple payloads rises or becomes significant, then the manipulator approach can be added as a later development.

In summary these are the recommendations for retraction/stowage:

1. Select the pivot mechanism approach as the primary EOS orbiter mode for payload retraction/stowage, deployment.

2. Kit the following:

   a. Simple minimum degree of freedom "manipulator" for use in assisting the retraction of small satellites into the cargo bay

   b. Clamp devices or rotating hinge mechanisms for use with large payloads that structurally cannot accept retention devices.

SECTION 3. DATA MANAGEMENT ACTIVITY GROUP SUMMARY

This section is an extraction and condensation of the significant analysis results from the following four interfacing activities:

- o COMMUNICATIONS
- o RENDEZVOUS
- o STATIONKEEPING
- o DETACHED ELEMENT OPERATIONS

The detail trades and analyses for each of the above interfacing activities are contained in Volume II Part 3 supplemented by Appendix A and Appendix B.

Five topics will be used to convey the pertinent study results:

- . Alternate Approaches
- . Design Concept Models
- . Performance Capabilities
- . Preferred Approach Selection
- . Design Influences

A separate Guidance & Control study was conducted and documented in Appendix A1. This study deals with the commonality of hardware for the functions of (1) state vector update, (2) attitude determination, and (3) line-of-sight tracking. The significant results from this study will be included in each of the interfacing activity summaries.

An additional detail study was also conducted and documented in Appendix A3. This study contains the trade data for (1) establishing the preferred communication links, (2) selection of the modulation/demodulation techniques, and (3) a technology investigation of microwave pre amps. The results of these investigations are summarized in the Communications paragraph (3.1).

DATA MANAGEMENT GROUP SUMMARY

DESIGN INFLUENCES	DRIVERS: PRIMARY	DRIVERS: SECONDARY
SCANNING LASER RADAR • RANGE & RANGE RATE — EOS, MANNED TUG, MSS PASSIVE REFLECTORS • ALL ELEMENTS	RENDEZVOUS STATIONKEEPING	MATING
SPACE CONTROL • ON-BOARD DATA PROCESSING - MSS ONLY • 3 ELEMENTS IN CONJUNCTION - MSS WITH TUG & RAM	RENDEZVOUS STATIONKEEPING	DETACHED ELEM OPERATIONS
INDEPENDENT CONTROL • HORIZON SCANNERS • IMU • STAR TRACKERS — EOS, MSS, TUG (SELECTED MISSIONS)	RENDEZVOUS STATIONKEEPING	DETACHED ELEM OPERATIONS
GROUND CONTROL • >75 N MI - ALL ACTIVE ELEMENTS	RENDEZVOUS STATIONKEEPING	—
S-BAND • OMNI ANTENNA • 1 MBPS ALL ELEMENTS	COMMUNICATIONS DET. ELEM. OPS.	ATTACHED ELEM OPERATIONS
Ku-BAND • DIRECTIONAL ANTENNA • 10 MBPS • VHF ORDER WIRE — MSS SELECTED RAM's, SAT	COMMUNICATIONS DET. ELEM. OPS.	ATTACHED ELEM OPERATIONS

S-band, Ku-band, and VHF communications links, which are compatible with the study definitions of the ground network and TDRS, are adequate for the transfer of data between elements and to ground. Because of the additional complexity (directional antenna) associated with Ku-band links this band was recommended only when the data transfer rates required the bandwidths of the TDRS.

Normally ground control was the preferred concept for operations between elements at relative distances of greater than 50 to 75 nautical miles. At lesser ranges a scanning laser radar on one of the elements was preferred for range and range rate information. Autonomous operations capability was preferred for the MSS, EOS, and selected tug missions.

3.1 COMMUNICATIONS

The communications interfacing activity encompasses the transfer of information between elements and to and from ground via communications links. Included in this information flow are voice, video, analog data, digital data, command/control digital signals, ranging signals, and tracking data. Each part of this information flow is an integral part of other interfacing activities and is used to accomplish a specific requirement of these other activities. Communications provide the tool to transfer the necessary information between elements.

ALTERNATE APPROACHES

Three fundamental communication link approaches are applicable for earth orbiting elements (Figure 3-1). They are (1) element to ground, (2) element to tracking and data relay satellite (TDRS), and (3) element-to-element. The first two approaches are dependent upon the characteristics of the Ground Network and TDRS. For the purpose of this study, the Ground Network and TDRS models developed by the Space Station Task Group (Reference Appendix C DS-504) will be used exclusively. It is likely that low ($\leq$10 Kbps) and medium data rates ($\leq$1 Mbps) will be handled by the Ground Network. TDRS could handle low data rates on VHF and up to 50 Mbps or Television on Ku Band. Requirements of individual elements will dictate which is used. TDRS can provide more nearly continuous communications than the Ground Network model. An operations constraint that is imposed by the TDRS model is that all communications utilizing TDRS must flow through the TDRS ground control center. This is true for ground to element communications as well as element to element communications even if both elements are within line-of-sight of a single TDRS.

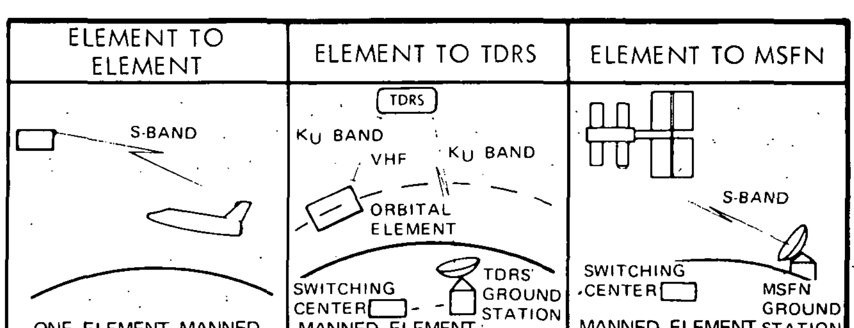


Figure 3-1. Communications Alternate Approaches

Element-to-Ground and Element-to-TDRS Links

The links between orbital elements and the Ground Network or TDRS are illustrated in Figure 3-2. As indicated, the Ground Network uses S-band for communications. TDRS uses VHF for voice and low data rates normally associated with command signals and Ku-band for high data rates including television transmission.

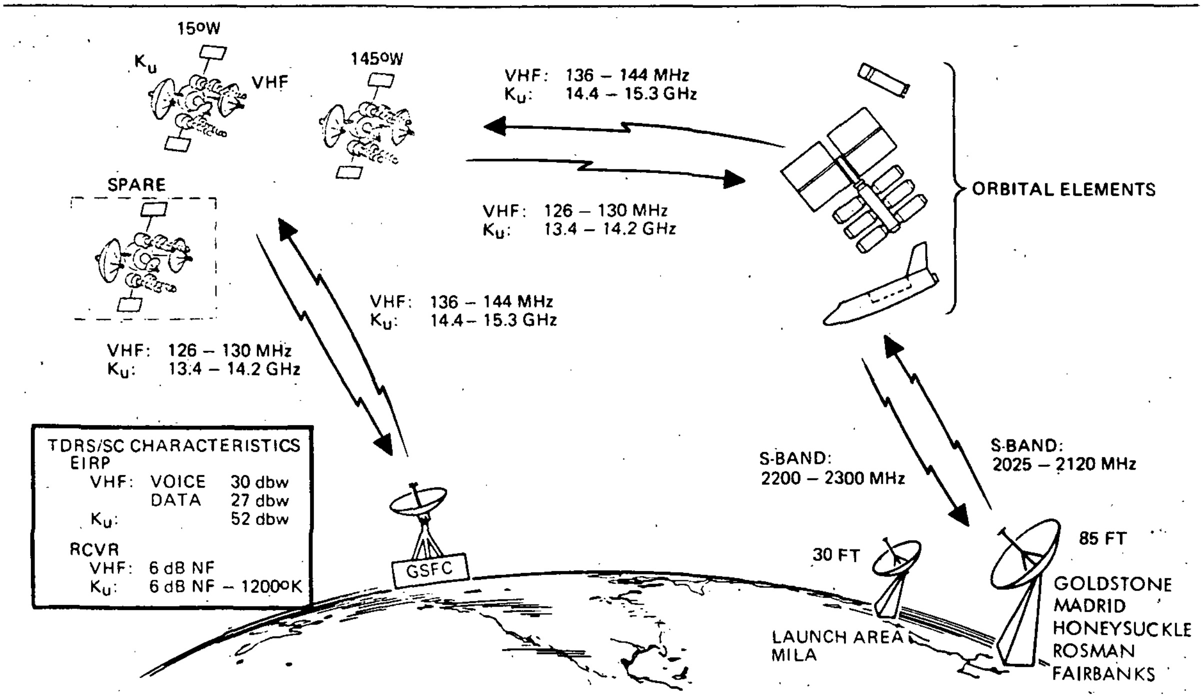


Figure 3-2. Ground Network and Synchronous Satellite Model (TDRS)

Element-to-Element Link

Appendix A3 delineates the trade study made that defines VHF, S-band and Ku band as the most desirable frequencies for element-to-element communications link. This provides compatibility with the ground and TDRS and the required performance.

A discussion of a modulation/demodulation techniques included in Appendix A3 results in the recommendation for techniques compatible with Ground Network System. PRN range code directly PM (PSK) modulates the carrier, digital data is PM (PSK) modulated on a 1.024 MHz sub-carrier and voice FM modulates a 1.25 MHz sub-carrier. These sub-carriers PM modulate the RF carrier. Direct carrier PM (PSK) modulation is necessary for high data rates (1 to 50 Mbps). The PCM/PSK/PM technique described above can be used for simultaneous ranging and data transfer for medium data rates.

In order to provide the necessary range and range-rate accuracies at close ranges (50 nautical miles to dock) for rendezvous, stationkeeping, and docking a laser radar system must supplement the PRN S-band range system at ranges less than 75 nautical miles.

DESIGN CONCEPT MODELS AND PERFORMANCE CAPABILITIES

Parametric, analyses and design concept trades were conducted at VHF, S-, X-, C-, and Ku-band frequencies. There were no significant advantages to utilization of frequencies other than VHF and Ku-band (TDRS links) and S-band (ground network link). All currently defined communication requirements can be adequately accommodated at these frequencies.

A parametric study was performed to establish the hardware requirements on orbital elements operating up to altitudes of 500 nautical miles. State-of-the art communications equipment was assumed in the calculations. The analyses indicated that only omni antennas were required on the orbital elements for VHF and S-band communication links. However, Ku-band links require a gimballed directional antenna (3-foot diameter) on the orbital elements.

Analysis of the data transfer requirements indicated that only selected RAMS's, satellites, and the MSS require Ku-band communication capabilities. All other element data rates were within the 1 Mbps data rate capacity of the S-band ground network system. Low data rates (1-10 Kbps) could be transferred through the TDRS VHF link. It would be highly desirable to include VHF capability in the ground network system. The preferred data links capabilities are summarized in Table 3-1.

Table 3-1. Data Link Capabilities

	Forward Link (Up Link)	Return Link (Down Link)
S Band* (with ground)	1000 bps voice	51.2 kbps voice television (FM baseband 1 MHz)
Ku Band*	100-1000 bps and data up to video plus voice	Greater than 1 Mbps up to 50 Mbps and/or video plus voice
VHF (with TDRS)	100-1000 bps plus voice	100-10,000 bps plus voice

*Both S- and Ku-band also provide the capability for PRN ranging simultaneously with other signals.

VHF Transmission

VHF is used for low data rates, voice links, TDRS order wire service, and element wake-up service. Omni-directional antennas (whip type) associated with a 25 watt, solid-state transmitter and an element 1200 K receiver system temperature provides sufficient performance for the required links. The link with TDRS requires a spread-spectrum modulation technique that was established to reduce multipath problems. The VHF link, either between elements or between element and TDRS is usable for single duplex voice channels, command digital signals, and low data rate (≤10 kbps) telemetry signals.

S-Band Transmission

S-band is used for medium data rates (up to 1 Mbps), voice links, and Apollo quality television service. Operation with ground stations requires relatively low power (less than 5 watts), omni-directional antennas and receiver noise temperatures of 1500 K to 2000 K. Such a design is possible because of the ground station parameters that include an 85-foot diameter (51 db gain) antenna, a 10 or 20 kw transmitter power and ground receiver system noise temperature of 125 K. Element-to-element links, however, may require hi-gain directional antennas and transmitter powers up to 100 watts according to the service and separation range.

In order to keep the transmitter power within reasonable state of the art for solid state equipment and enable use of omni-directional antennas it will be necessary to limit separation ranges to 150 nautical miles or less according to data transfer requirements. This would put a ceiling of approximately 30 kbps on digital data transfer. This assumes the use of a 30-watt solid-state transmitter (within present day technology) and an omni-directional antenna. When element-to-element requirements dictate higher data rates at longer ranges, a directional antenna can be used with a 30-watt transmitter. With a 5-foot parabolic antenna (28 db gain), 1 Mbps may be transferred over a range of 500 nautical miles. There are few cases where high data rates (≥50 kbps) need be transferred over relatively long ranges (≥150 nautical miles). RAM and MSS are the elements involved with these higher rates. In these cases, it is more effective to use Ku-band when the transfer of TV and data rates from 1 Mbps to 50 Mbps are involved.

Ku-Band Transmission

Ku-band is used for high data rates, voice links, and good quality black and white or color TV. It is needed for operation to ground through the TDRS. One of the major advantages of TDRS is the capability to provide almost continuous orbital communications with low earth orbit elements. Communications with ground direct could result in contact gaps as well as relatively short (less than 15 minutes) contacts per orbit. This assumes the 5 station ground network established by NASA (reference DS-504). Ku-band does require a directional antenna whether it is being used for element-to-element communications or element-to-TDRS-to-ground. It is, therefore, only recommended when either the data rate or continuity of contact with ground makes it necessary. The longest range link is to TDRS (approximately 23,000 nautical miles).

Utilization of a 25-watt transmitter with a 5-foot parabolic antenna (45 db gain) can satisfy up to 25 Mbps digital data transfer to the TDRS. A receiver with a Tunnel Diode Amplifier (TDA) providing approximately a 1200 K noise temperature with this 5-foot antenna is usable for all TDRS-to-element link requirements. The maximum demand in this direction is 500 kbps or 4.5 MHz color TV. Element-to-element Ku-band operation would probably be supported by the same equipment used for element-to-TDRS contact. Color TV (4.5 MHz) could be supported to 2000 nautical miles with a 25-watt transmitter, a 1200 K receiver noise temperature, and 20 db gain horn antennas on each end of the link.

When Ku-band is needed, it is recommended that a 25-watt transmitter (with a traveling wave tube amplifier (TWTA)), a 5-foot (45 db gain) parabolic antenna, and a TDA receiver front end (1200 K noise temperature) be used. These are all within present technology as displayed in Appendix A3. The directional antenna must be a tracking type because of the narrow beamwidth ($\approx 1°$ at 3 db points) and capable of either auto-track or computer programmed tracking.

Modulation

As detailed in Appendix A3, it is recommended that modulation techniques compatible with the ground network be utilized for both S- and Ku-band links for data transfer up to 1 Mbps. This uses subcarriers for voice and digital data and direct carrier phase modulation for the PRN ranging signal. For higher data rates (up to 50 Mbps) direct carrier PSK should be used for the digital data. High-quality TV, black and white or color, will direct FM modulate the carrier.

Tracking and Ranging

Tracking and ranging, for ranges over 75 nautical miles between elements, utilizes the standard PRN ranging system as mechanized by the existing NASA ground network. This provides the necessary accuracy for ranging and range-rate measurements and can provide orbital parameters by making successive range measurements from the ground stations. This requires a coherent transponder on the measured vehicle which accepts the range code signal from the interrogating station and re-transmits the signal at another carrier frequency that is coherent with the incoming carrier and at a known fraction thereof. A further discussion of this system is included in the analysis of Volume II, Part 3, section 1.0. Typical accuracies after 1-1/2 orbits with measurements from four NASA ground stations are:

Position	Errors (1σ)
R range	320 ft
T	370 ft
N cross range	360 ft
$\dot{R}$ range - rate	0.53 ft/sec
$\dot{T}$	0.37 ft/sec
$\dot{N}$	0.42 ft/sec

Utilizing similar measurement techniques with TDRS on Ku-band decreases these accuracies by a factor of three or more according to the length of time taken for measurements. Even these accuracies are, however, satisfactory for measurements when space elements are more than 75 nautical miles apart.

At ranges less than 75 nautical miles to docking, during either station-keeping, rendezvous or docking maneuvers, where accuracies must improve by orders of magnitude, a scanning laser radar system can provide the required precision. The measuring vehicle requires the scanning laser radar and the measured vehicle a set of corner cube optical targets for reflection purposes. Proper use of reflector configuration can actually provide not only range and range rate measurements but locate the docking port and provide an attitude measurement. Detailed discussion of the scanning laser radar is found in Mating (Volume II, Part 2, Section 1.0) and in Rendezvous (Volume II, Part 3, Section 2.0). Typical accuracies for ranges of 75 nautical miles and less are:

Range: ±4 in. or ±0.02 percent, whichever is greater

Range-rate: ±1/2 in./sec or ±1 percent, whichever is greater

Communication Equipment

An element that would provide a full complement of external communications capability would contain the following:

1. Ku-Band Receiver and Transmitter with a 5-foot parabolic dish antenna. The receiver would have a noise temperature of 1200 K and the transmitter would provide 25 watts of RF power to the antenna.

2. S-Band Receiver and Transmitter with a semi-directive antenna. The receiver would have a noise temperature of 800 K and the transmitter would provide 30 watts of RF power to the antenna.

3. VHF Receiver and Transmitter with an omni-directional antenna. The receiver would have a noise temperature of 1200 K and the transmitter would provide 25 watts of RF power to the antenna.

4. Active elements would contain a Scanning Laser Radar System. Passive elements would have passive optical corner cube reflectors.

These characteristics and the parameters thereof would be subject to modification according to link capacity requirements. The requirements analysis of Volume II, Part 3, Section 1.0, provides further details for an understanding of the choices for particular element pairs and elements.

Element transmitters should contain the capability to reduce power output in a step function. This is used in element-to-element communications as the range between elements decreased to avoid receiver overloading. When using S-band or VHF, omni-directional capability that can be obtained without changing element attitude must be implemented by the use of more than one antenna. This could mean either switching to several antennas or providing a receiver/transmitters at each antenna.

Complete system mechanization may mean more than one frequency operation in a particular band according to the number of different frequency links required or the number of simultaneous links necessary. The MSS, for instance, needs the capability to contact five different terminals; two RAM's, a ground station, the EOS, and the TDRS.

DESIGN INFLUENCES AND PREFERRED APPROACH

For the communications activity, choice of a preferred approach, i.e., (1) element-to-element, (2) element-to-ground direct, or (3) element-to-ground via TDRS is appropriate only for the choice between the ground links. During any element mission, communications links must be established between the element and another element or between the element and ground. An element-to-element link can only be effectively accomplished by a direct link. The present TDRS system does not have the capability to support a link between two elements directly through the TDRS. All element communication to TDRS must flow through the TDRS ground control center. Thus, the signal from one element must be to TDRS, TDRS to ground, switched from ground to TDRS, and then to the other element pair. Similar attempts to provide such a link through the ground network could be more complicated.

Therefore the following is recommended:

- Use direct element-to-element RF communication for the case where two elements must have direct contact.

  Rationale. All elements or element pairs can utilize this link during Rendezvous (3.2), Stationkeeping (3.3), and Detached Element Operations (3.4) to support mission activities.

- Use the TDRS-to-ground link with either Ku-band or VHF, depending upon data rate or base band bandwidth.

  Rationale. TDRS provide a larger percentage of communications continuity then the ground network.

  High data rates (1 to 50 Mbps) or analog signals (4.5 MHz TV) nessitate Ku-band because the present S-band ground network stations cannot handle these bandwidths.

- Provide a direct to ground link as an alternate to ground via TDRS.

  Rationale. With the current five station ground network contact time to ground may be severely limited for certain orbits.

  The current TDRS model (two satellites) is limited to 4 Ku-band and 40 VHF users which can present a scheduling problem.

  Tracking and ranging of satellites is more accurate from ground stations.

In conclusion, it is recommended that each element be equipped to provide communication to other interfacing elements direct, to ground direct, and to TDRS when necessary for bandwidth or continuity reasons. The selection of all three approaches provides the major reason for the recommendation of VHF, S- and Ku-bands as the only alternate frequencies to consider for communications. By using these frequencies for element-to-element links, a commonality of equipment is accomplished. These frequencies, tracking/ranging, and modulation techniques are compatible with the ground use, either direct or via TDRS. Appendix A3 defines the trades made to establish this recommendation.

A review of advantages accrued by this overall approach indicates many other supporting factors as follows:

- No breakthrough in technology is required to implement the necessary element communications terminals.
- S-band equipment compatible with existing ground network systems is presently available.
- The addition of RF power to 30 to 35 watts may require new design for space application. Solid-state 30-watt S-band equipment has already been built and requires no new development.
- Ku-band equipment is not in general use but receiver and transmitter components presently exist to support the development and design of receivers with the noise figures estimated in this study (1200 K) and transmitters with power outputs to 25 watts. See Appendix A3 for further details. The development of TDRS will hasten the availability of Ku-band equipment and stimulate performance improvements.
- VHF is obviously a tried and developed frequency band. Checkout and maintenance of this equipment is well defined and much knowledge already exists to ensure high reliability.
- One of the advantages of utilizing commonality between approaches is the provision of backup links. The capability to work with either TDRS or ground improves the reliability of mission operations. Safety is enhanced by providing the second link in the case of unforeseen problems.

Scanning Laser Radar

The requirement for accurate knowledge of relative position, relative range-rate and angles between elements for Rendezvous, Stationkeeping, and mating leads to the choice of a scanning laser radar (SLR). Because of the precision of measurement accuracy, it is capable of support of these activities as well as an automatic docking operation between two unmanned satellites. Although the scanning laser radar is useful to a maximum of 75 nautical miles, it provides measurement accuracies at this range better than necesaary but also has the precision for docking operations or close-in rendezvous and stationkeeping. At ranges greater than 75 nautical miles, S-band PRN range is sufficiently accurate, either by element-to-element relative measurement or from a ground station.

Element Pair Hardware Selections

Table 3-2 is a compilation of all element approaches by major category. Consideration was given only to earth orbital operations. Lunar missions will add requirements to the RNS and CPS.

Table 3-2. Approach Selection

Element		Operates With	Ku-Band 25-watt 5 ft Ant	S-Band 30-w Transmitter 3 ft Ant	S-Band 30-w Transmitter Omni	VHF 25-watt Omni
EOS		EOS, Tug, RAM, MSS, CPS, RNS, OPD, Sat	-	-	X	X
Tug		EOS, Tug, RAM, Sat, MSS, CPS, RNS, OPD	-	-	X	X
RAM		EOS, MSS, Tug	X	-	X	X
MSS		EOS, Tug, RAM	X	-	X	X
RNS		EOS, Tug, OPD	-	X*	X	X
CPS		CPS, EOS, Tug, OPD	-	X*	X	X
OPD		EOS, Tug, CPS, RNS	-	-	X	X
Sat		EOS, Tug	X	-	X	X
Element	Element	Element	X	X	X	X
Element	Element	Ground direct	-	X	X	X
Element	Element	TDRS to ground	X	-	-	X

*Shown to indicate that this capability will probably be available to support lunar missions. Omni capability will support all earth orbit operations.

An examination of the orbital elements (by groupings) discloses that only two require Ku-band/TDRS operation. These are the RAM and MSS elements. All others can perform all necessary communications by S-band direct to ground or by VHF through TDRS to ground.

RAM and MSS elements require the Ku-band link to TDRS to ground to provide the necessary bandwidth for the high data rates generated for real time and data dump from these elements. RAM will have some experiments that generate up to 35 Mbps data. Storage on board will relieve some of the demand but not sufficient to allow S-band direct to ground for high data rate and wideband TV. This is limited by bandwidth as well as reduced contact time. Color television and data rates of at least 2 Mbps from MSS along with high daily data dumps need the Ku-band channel bandwidth on TDRS.

Although continuity of contact may be a problem for other elements in certain missions, a TDRS/VHF link can satisfy their normal low data rates and voice channels to provide high percentage of orbit contact time even at low orbits. The result is that most elements can satisfy communication needs with only S-band and VHF equipment, both with omni-directional antennas. By using PRN transponders for both ranging and communications, all long range (greater than 75 nautical miles) tracking/ranging requirements can be met. Ground stations can track to 75 nautical miles separation.

A detailed table for each element listing the characteristics required for earth orbital operations is contained in Volume II, Part 3, Section 1.0, under paragraph 1.7.

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3.2 RENDEZVOUS

The purpose of the rendezvous activity is to conduct orbital maneuvers (other than orbital maintenance) to either establish or alter a prescribed range/range rate relationship between two orbiting elements. The predominant operational mode is to conduct thrusting maneuver on one element to position that element within close proximity of another element.

Under a broad definition of rendezvous, the injection and placement of an element at a prescribed spatial location could be defined as rendezvousing with a point in space. This operational mode involves only one orbital element and, therefore, is not considered further in this study.

Rendezvous operations may either commence from a stationkeeping mode or terminate in a stationkeeping mode. Thus the range dispersion between elements varies from a few thousand feet to several thousand miles. The rendezvousing elements may or may not maintain line of sight during the operation.

ALTERNATE APPROACHES

Three alternate approaches were synthesized and evaluated. These approaches are illustrated by Figure 3-3.

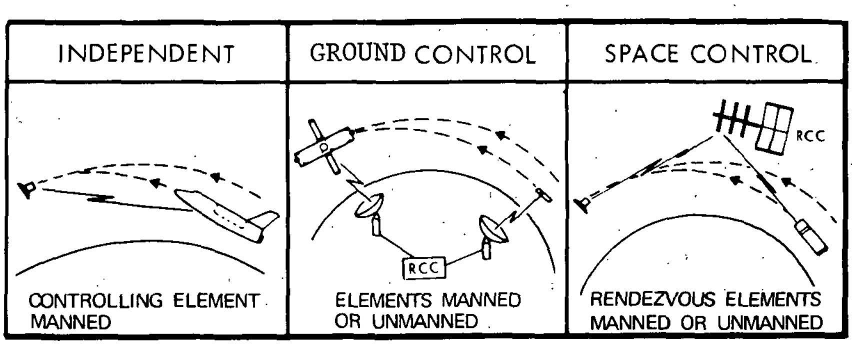


Figure 3-3. Rendezvous Alternate Approaches

The key functions that must be accomplished are: (1) attitude determination, (2) state vector update, (3) flight control computation, (4) relative range and velocity determination, and (5) command, control and data transfer links.

Independent Operation

This approach requires the conduction of all rendezvous operations solely by the orbiting elements. It is assumed that either continuous or at least adequate periodic line of sight exists between the vehicles. Use of ground relay links between elements is not considered in this approach. Command and control of the operations can be accomplished by either the passive (target) or active (maneuvering) element. The elements could be manned or unmanned.

Ground Control

In this approach all command and control is accomplished by a ground control center. The orbital elements require certain unique sensors but essentially only execute the commands from the control center. Neither range between elements nor communication gaps are considered a constraint in this approach. Appropriate mission planning is assumed to be feasible to circumvent the contact dropouts. Either the ground network or TDRS are considered as viable control centers for this approach.

Space Control

This approach involves three orbital elements, the two elements that are rendezvousing and a third element that functions as the control center. This orbital control center is required to conduct all the operations that the ground control center of the second approach must perform. This approach will have more stringent constraints on both range and line of sight to the rendezvousing elements. Continuous line of sight is not mandatory; however, the probability of long duration contact drop outs at long ranges is much higher with this approach. Use of ground stations for data relay purposes is not considered in this approach.

The major difference between these approaches is the location of the command and control center. These three distinct approaches were selected for evaluation to assist in a more detailed examination of the design influences of the unique function of each approach. Hybrid combination of the approaches are considered during the design impact assessment associated with the preferred approach selection for each element pair.

DESIGN CONCEPT MODELS AND PERFORMANCE CAPABILITIES

The design concept for all approaches and ultimately the design impact on the orbital elements are predicated upon the following key functional requirements for accomplishing rendezvous:

1. Attitude Determination
2. State Vector Update
3. Flight Control Computation
4. Relative Range and Velocity
5. Command, Control and Data Transfer Links

Table 3-3 summarizes the hardware complement of rendezvousing elements for the critical functions for the three approaches.

Table 3-3. Function/Hardware Versus Approach

	INDEPENDENT	SPACE CONTROL	GROUND CONTROL
Attitude Determination Star Tracker/Horizon Scanner and IMU	Both Elements 2K (32 Bit)	All Three Elements Same	Both Elements Same
State Vector Update Star Tracker/ Horizon Scanner Computer Deltas	One Element 10K (32 Bit)	Control Element Only 15K (32 Bit)	None
Flight Control Computation Computer Deltas	One Element 2K (32 Bit)	Control Element Only 2K (32 Bit)	None
Range/Range Rate Long Range Transmitter (VHF or S-Band) Antenna Transponder Computer Deltas Short Short Range Lasar Radar Passive Reflector	 One Element Omni-Both Elements Both Elements 4K (32 Bit) One Element One Element	 Control Element Omni-3 Elements Both Elements 6K (32 Bit) Same Same	 None Omni-Both Elements Both Elements None Same Same
Communication Links	VHF or S-Band w/Omni	Same	Same

Attitude Determination

Rendezvous operations are independent of the relative attitude between the elements involved. However, the attitude of any element required to perform delta V maneuvers must be known to sufficient accuracy to permit efficient thrusting maneuvers. Attitude accuracy is only one factor in the overall error budget for determining propellant consumption rates. Current operational hardware and thrusting maneuvers computations can minimize the affect of attitude inaccuracies. An evaluation of alternate concepts is presented in Appendix A1.

Consideration of this activity and the attitude determination function in conjunction with other activities and related functions resulted in the selection of a star tracker/horizon scanner concept to provide both inertial and earth reference attitude information. Accuracies of ± 0.5 degree can be readily obtained. Attitude reference can be maintained by an inertial platform (IMU) or strapdown gyros. Attitude maneuver by either positive expulsion or momentum exchange devices are acceptable.

State Vector Update

In both the independent and space controlled approaches at least one orbital element must include the capability to perform state vector updates. The sensors required are the same as for attitude determination; namely, a star tracker and horizon scanner. On-board computational capability is also required to calculate the ephemerids from the sensor data. Storage capacity and computer complexity for this task is not considered to be a significant design influence.

In addition to determining its own state vector, the orbital element must also determine the state vector of the other element (independent approach) or the other two elements (space control approach). This imposes an additional tracking and ranging requirement, as well as additional storage capacity and complexity on the orbital computer system.

A representative laser radar was synthesized that is adequate for ranges from 25 nautical miles to essentially zero range. For longer ranges current operational VHF or S-band ranging are proposed and are compatible with communication link requirements for other functions.

The ground control approach could use either the ground network or TDRS for state vector updates. Either concept can provide position data to within one nautical mile uncertainty. Only a transceiver would be required on the orbiting elements.

Note: The operational limitations to these concepts is explained in paragraph 2.4 of Volume II, Part 3, Section 2.0.

Flight Control Computation

There are two aspects of flight control that must be considered: (1) thrust vector control (TVC), and (2) computation of maneuver requirements. On-board automatic thrust vector control is always preferred. On the Apollo program, manual TVC on manned vehicles was demonstrated but was considered as a backup mode. Although an astronaut can be trained to perform this function, the margin of safety and maneuver efficiency is significantly less than for an automatic TVC. Remote control of TVC was also incorporated in the Apollo program. Simulation runs indicated that this technique was feasible. However, this concept was considered as a last ditch emergency mode of operation. It obviously requires continuous LOS and extensive telemetering of element performance data. This technique also has a reduced margin of safety maneuver efficiency. Self-contained automatic TVC on both manned and unmanned maneuvering vehicles is the preferred design concept in all cases.

The computation of the desired maneuver, ignition time, duration, pointing, etc. can be performed effectively by an on-board computer or by a ground computer. In order to minimize on-board equipment, complexity, checkout and maintenance, and dedicated usage the preferred location, in general, would be ground control.

Relative Range and Velocity

The relative range and range rate between rendezvousing elements varies from thousands of miles and feet per second to only a few miles and less than a foot per second. At the upper end of the spectrum any of the three approaches can adequately perform the task with demonstrated VHF or S-band ranging hardware. Transponders on the target elements are mandatory in order to limit the power and antenna requirements on the tracking centers to reasonable requirements.

The primary differences in the three approaches for long range operations are the potential gaps in the communications. However, gaps are tolerable because tracking and ranging need not be on a continuous basis. If TDRS is used in the ground approach, it does afford almost continuous coverage. Use of the ground network wil result, in some cases, communication gaps of longer than one orbit and also will require control handover between ground stations. Space control and independent approaches will result in even more sporadic and longer interruptions of tracking. However, with detailed mission planning these shortcomings can be accommodated.

At ranges of a few nautical miles safety of operations become an overriding factor. Accuracies in both range and range rate become marginal. A scanning laser radar (SCR) is proposed for all element pairs involved in rendezvousing. This same SCR is used for related functions in Stationkeeping and Mating. The SCR is described in detail in Appendix A1. Typical accuracies for the design concept model are:

Range:	0 to 75 nautical miles $\pm$ 0.02% or $\pm$ 10 cm (whichever is greater)

Range Rate: 0 to 1 km/sec $\pm 1\%$ or $\pm$ 1.0 cm/sec (whichever is greater)

These performance characteristics exceed the requirements for close range rendezvous activities.

Command, Control, and Data Transfer Links

Communication link calculations are detailed in Volume II, Part 3, Section 1.0, Communications. In all three approaches the requirements for rendezvous data transfer is not the determining factor in establishing link requirements for range or data rates. VHF, S-band or Ku-band communication links can accommodate rendezvous communication link requirements.

The one unique aspect of data links associated with rendezvous is the highly desirable real time link between the maneuvering element and the control center during thrusting maneuvers. Note that this is not a mandatory requirement. Both manned (CSM TEI) and unmanned (Apollo spacecraft 011 development flight) thrust maneuvers have been performed while not in contact with the control center.

DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

A generalized evaluation of the three rendezvous approaches is presented in Table 3-4. The primary factors that influence the preferred approach selection are:

1. Operational ranges between elements
2. Complement/complexity of equipment on orbital elements
3. Safety of operations

A detailed description of each factor is contained in paragraph 2.7 of Volume II, Part 3, Section 2.0.

Table 3-4. Rendezvous Approach Evaluation

Consideration	Independent	Ground Control	Space Control	Remarks
Manned/Unmanned Elements	✓	✓	✓	All approaches are applicable
Operating Range				
Line-of-Sight	✓	✓	✓	
Beyond LOS	NA		Limited*	
Attitude Determination	✓	NA	NA	Orbital Element must determine own attitude
Navigation Update				
Accuracy	Same	Same	Same	
Onboard Complex.	Nominal	Minimum	Maximum	
Technology	SOA	SOA	SOA	
Operational Safety				
Long Range	✓	✓	✓	
Close Proximity	Better	Good	Adequate	Based upon Reasonable equip.
C/O & Maintenance	Nominal	Minimum	Maximum	Elem Equip. Only
Relative Cost				
Development	Nominal	Minimum	Maximum	Elem Equip. Only
Operations	Minimum	Nominal	Maximum	Total Operation
Operations Impact				
Near Term	None	None	None	
Long Range	None	Could be major	Minor	Requires priority scheduling of activity
Communication Requirements	1-10 KBPS	1-10 KBS	1-10 KBS	Available comm links adequate

*Note: Unique case where control element is within LOS of other two elements but rendezvousing elements are not within LOS of each other.

Preferred Approach Selection by Element Pairs

The preferred approach selections for rendezvous are summarized in Table 3-5. These selections were based upon the currently proposed traffic models through 1990. However, as the specific orbits of various program elements become firm, ground control may be required to assume an even more predominant role. At this juncture of the space program traffic is comparable to air traffic of 20 to 30 years ago. Traffic in "preferred" orbits may require extensive "space traffic" control provisions which would place excessive computational, memory, and tracking requirements on all orbital elements.

All facets of the preferences for rendezvous are compatible with similar aspects of stationkeeping and detached element operations. The design concepts are in accord and utilize the same equipment proposed for communications, mating, and separation for the same or similar functions.

Table 3-5. Rendezvous Preferred Approach Selection

Element Pair	Preferred Approach	Rationale
EOS TUG, RAM, Satellite, MSS, CPS, RNS, CPD, OLS	Independent	Preplanned operation, ground network, communication GAPS, close proximity terminal range, manned element
MSS TUG and RAM TUG or RAM	 Space Controlled Independent	 Nature of operations, Nature of operations, close proximity terminal range manned element
TUG* OPD, CPS, RNS, Satellite, RAM	Ground Control	Wide ragne dispersion, minimize on-board equipment, frequent operations beyond line-of-sight
CPS/RNS* (Manned/Unmanned) OPD	Ground Control	Wide range dispersion, minimize on-board equipment, frequent operations beyond line-of-sight

*Direct measurement of range/range rate between elements required at close range (LSR preferred); manual override capability required when one element is manned.

Design Influences

Based upon the preferred approach selection the resulting design influences on elements involved in rendezvous operations are summarized in Table 3-6. The EOS and the MSS require the full complement of equipment to conduct all the potential rendezvous operations that they will be involved in. The primary driver on the EOS is its requirement for quick response time and thus independent operation. The MSS, by definition, is an independent space facility and thus must accommodate all the potential operations.

The tug normally is commanded by ground control in its rendezvous operations. However, one class of missions will require the total complement of equipment except for command links to the target. This class consists of a quick response operation in conjunction with the EOS for retrieval of a satellite. It is not recommended that all ground based tugs incorporate this equipment complement.

The CPS or RNS are limited in their rendezvous operations in earth orbit. (Lunar operations may impose different requirements.) Ground control will perform all ranging, state vector determination, and thrust vector determine functions for both TLI and EOI operations. This is based upon the assumption that these two elements are non-piloted. If piloted independent capability would be included.

Detached RAM's, especially in conjunction with the station, will be required to make rendezvous maneuvers. Therefore, their equipment complement reflects the associated functions when commanded from another element.

Satellites are considered to be non-maneuvering (excluding attitude control) elements. Therefore, their equipment complement is indicative of a passive but cooperative target.

The OPD is also considered a passive-cooperative target in rendezvous operation. The LSR is included in the OPD list for rendezvous with cislunar shuttles.

Table 3-6. Rendezvous Design Influences

	EOS	Tug	CPS/ RNS	DRAM	MSS	Sate- llite	OPD
Star Tracker	√	√	√	√	√		
Horizon Scanner	√	(1)			√		
Attitude Reference System	√	√	√	√	√		
Scanning Laser Radar	√	√			√		√
Passive Reflector	√	√	√	√	√	√	√
S-band Omni	√	√	√	√	√	√	√
S-band Transponder	√	√	√	√	√	√	√
S-band Ranging	√	(1)			√		
State Vector Computation	√	(1)			√		
LSR Tracking and Ranging	√	√			√		
S-band Trackings and Ranging	√	(1)			√		
TVC Computations	√	(1)			√		
TVC Capability	√	√	√	√	√		
Command Link	√				√		

NOTES: (1) It is envisioned that some ground based tug missions will require reaction times that will not permit parking orbits stay time for ground track navigation and thrust vector updates. On these selected tugs independent capability, similar to the EOS, will be required.

3.3 STATIONKEEPING

The stationkeeping interfacing activity includes those operations required to maintain a prescribed orbital relationship between two elements. This relationship can include varying range, range rate and/or attitude between the elements.

The operating ranges between stationkeeping elements can vary from a few feet (inspection of one element by another) to thousand of miles (quiescent orbital storage of elements such as the CPS and OPD). However, the predominant modes of stationkeeping are concerned with post rendezvous/pre-mating operations and detached element operations. A final inspection/checkout of the elements to be mated would be conducted prior to initiation of the mating maneuvers. A RAM could be deployed from either an EOS or MSS to eliminate the environmental effects of the base element but maintain a prescribed relationship with that base for control/monitor purposes of the operations of the RAM.

ALTERNATE APPROACHES

The stationkeeping operation can be controlled using any of the following general approaches illustrated by Figure 3-4.

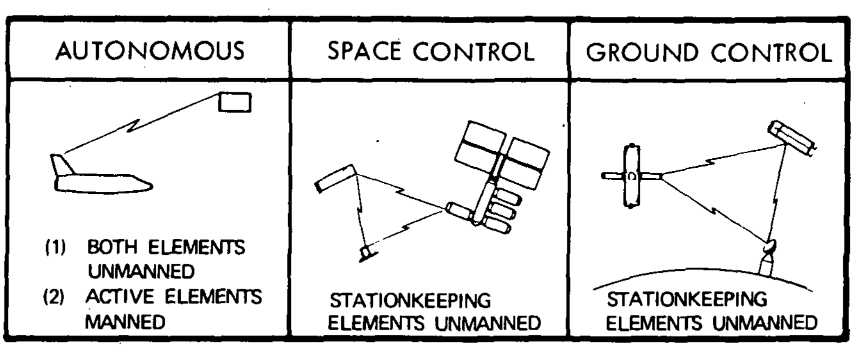


Figure 3-4. Stationkeeping Alternate Approaches

Autonomous - Both Elements Unmanned

Autonomous stationkeeping operations are conducted without support from external bases either space or ground. One element is in command of all the operations of both stationkeeping elements. It is equipped with automated systems that perform preprogrammed timing for all operations. Both elements have the capability to perform both attitude and orbital makeup maneuvers.

Autonomous - One Element Manned

When one of the autonomous stationkeeping elements is manned, it assumes command and control of all stationkeeping operations. Man takes over command and controls all operations in the same procedural sequence as in the unmanned autonomous approach. Both elements have the ability to perform both attitude and orbital makeup maneuvers.

Ground-Controlled

This approach employs complete ground control of all stationkeeping operations. Relative position information can be obtained by ground-tracking both vehicles or having one vehicle track the other and transmit the data to the ground. The ground computes the necessary correction maneuvers and transmits attitude and translation commands to the active vehicle which executes the maneuver. The communication links are either direct from ground stations or via TDRS. The ground-controlled concept is particularly suitable for a stationkeeping operation involving two unmanned vehicles or a single synchronous unmanned orbital vehicle.

Space-Controlled - Remote

This approach is characterized by being independent of the ground and intelligence and control of the vehicle(s) is included in a nonactive or non-maneuvering vehicle. This approach is comparable to the ground control approach but imposes additional functional requirements on the orbital elements. Two or more elements could be involved in this approach. For example, the stationkeeping operations of a detached maneuvering RAM could be totally controlled by a space station, or the station could control a space tug stationkeeping with a detached RAM for the purposes of inspection.

STATIONKEEPING FLIGHT MODES

Some alternate stationkeeping flight modes that could be utilized with any of the stationkeeping approaches previously mentioned are illustrated in Figure 3-5.

These various flight modes were investigated to determine their influence on the functional requirements of stationkeeping. The two tethered flight modes introduce significant increases in complexity and functional requirements, all of which are almost totally dependent upon the configuration and design concept of the elements involved. Therefore, this class of flight mode is more apropros as an analysis task for an individual element study. Tethered modes were not considered further in this study.

DESIGN CONCEPT MODELS AND MAJOR FUNCTIONS

The design concept models in all approaches are predicated on the methods used to provide (1) attitude determination, (2) state-vector determination, (3) relative position, (4) flight control computation, and (5) communication links. Table 3-7 summarizes the design concepts for each major function and approach.

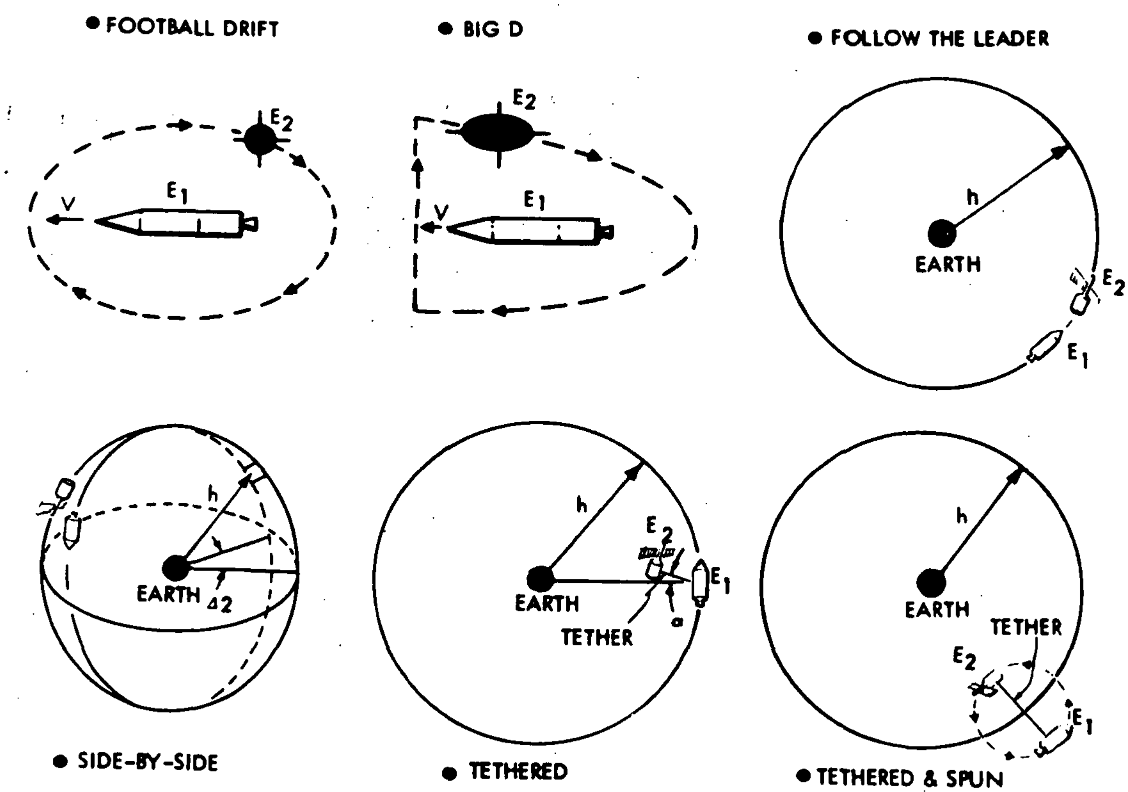


Figure 3-5. Alternate Stationkeeping Flight Modes

Table 3-7. Design Concept Summary

Operational Function	Design Concept	Approach: Autonomous	Space Controlled	Ground Controlled
Attitude Determination	IMU/Star Tracker/ Horizon Scanner	✓	✓	✓
State Vector Determination	IMU/Star Tracker			
	One Element	✓		
	Control Element		✓	
	Tracking and Ranging			
	One Element	✓		
	Control Element		✓	
	None			✓
Relative Position	VHF	✓	✓	
	S-Band	✓	✓	✓
	Laser	✓	(✓)*	(✓)*
Flight Control Computation	One Element	✓		
	Control Element		✓	
	Ground Element			✓
Communication Links	VHF	✓	✓	
	S-Band	✓	✓	✓

*Laser system is on stationkeeping elements

Attitude Determination

Both stationkeeping elements must maintain specific attitudes to fulfill either mission requirements and/or to ensure the orientation for delta V or attitude maneuvers. A guidance and control analysis (contained in Appendix A1) was conducted to establish an integrated concept for all related functions of the various activities. A common usage system consisting of an Inertial Measurement Unit (IMU), star tracker, and horizon scanner can provide sufficient attitude reference for all stationkeeping operations. The horizon scanner will facilitate earth coordinate relationship determination. Control authority could be implemented by either a positive expulsion concept or a momentum exchange concept. The selection would be based upon performance requirements other than those related to stationkeeping.

State Vector Determination

For the autonomous approach, state vector determination can be implemented by the IMU/star tracker/horizon scanner set of equipment to accuracies of one nautical mile position uncertainty. In the case of the separate control center approaches--space or ground--state vectors and orbital parameters are determined by measuring range and range rate data on each of the stationkeeping elements and computing the ephemerids based upon the known position of the control center. This imposes the requirement of the space control center to be capable of determining its own state vector.

Use of the ground network S-band system in conjunction with transponders on the stationkeeping elements will result in position uncertainties of approximately one nautical mile. Similar results can be obtained with an S-band system on the space controlling element. VHF ranging similar to the Apollo-LEM concept could also be used.

Relative Position

In all three approaches S-band will adequately provide relative position and velocity data at long range. However, when the two stationkeeping elements are within five nautical miles of each other, ambiguties in the space and ground control approaches commence. In close proximity operations such as inspection or premating operations, the S-band or VHF (between elements) techniques are no longer adequate regardless of the approach. Video could be used for the separate control center approaches. However, both of these design concepts require almost continuous monitoring. The preferred design concept is to incorporate laser scanning radars regardless of the approach.

In all three approaches the monitoring of the critical range/range rate parameters can be automated and thus alleviate a tedius and judgement task. In the separate control approach the data is telemetered to the control center. In the autonomous case direct readouts and alarms can be incorporated for the manned element option. Unmanned operations can be automated in the same manner as in the separate control centers.

An evaluation was conducted to establish the practicality of a scanning laser radar for the stationkeeping functions and is contained in Volume II, Part 2, Section 1.0, Mating. A concept within the state of the art was defined that can provide accuracies of ±6 inches (0.02 percent of range) and 0.1 foot/second (1 percent of range rate) up to 75 nautical miles. Therefore, the recommended design concept for determining relative range and range rate between stationkeeping elements at ranges ≤75 nautical miles is the scanning laser radar.

Flight Control Computations

The computational concepts are essentially the same for all three approaches. There are no unique computer requirements. Numerous hardware designs can provide the necessary storage and processing functions. The significant impact is the additional equipment that is required on the space elements for both the autonomous and space controlled approaches. Flight control computational capability is required independent of stationkeeping requirements, but navigation computation requirements are a delta and could impose additional storage or memory capacity requirements.

Communication Links

Although all three approaches require data links that have numerous options the selections are based upon the integrated communication link trades developed in the communications activity. Stationkeeping data transfer requirements are not the governing factor in the preferred approach selections of communications. Element-to-element communication (autonomous and space-controlled approach) requirements can be accommodated on VHF or S-band omni antenna links. Ground control links can be accomplished by utilizing the ground network S-band system with only omni antennas on the orbital elements.

Low resolution video (TV) is considered adequate for inspection purposes. The corresponding data rates can also be accommodated on the S-bank link with an omni antenna on the stationkeeping elements.

DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

The primary factors that influence the selection of a preferred stationkeeping approach are:

1. Type of stationkeeping mode
2. Range between elements
3. Design implications of the approach
4. Relative costs
5. Manning status of the elements

Table 3-8 presents an evaluation of the three alternate approaches. The detailed description of this evaluation is contained in paragraph 3.7 of Volume II, Part 3, Section 3.0.

Table 3-8. Stationkeeping Approach Evaluation

	Modes								Operating Range			Design Impacts/Complexity							Relative Cost			
	Detached Operations		Inspection		Premate		Quiescent Storage		Close Proximity	Long	Beyond LOS	Close Proximity	Long	Beyond LOS	State Vector Update	Computer Capacity	C/O & Maintenance	Technology	Development		Operational	
	M	U	M	U	M	U	NA	U											M	U	M	U
Autonomous	✓		✓		✓				Best	Fair	--	Low	High	--	High	--	Med	SOA	Med	--	Low	--
Ground Control	✓	✓		✓		✓		✓	Good	Best	Best	Med	Low	Low	Low	Low	Low	SOA	Low	Low	Med	Med
Space Control	✓	✓		✓		✓			Fair	Good*	Limited*	Med*	Med*	Med*	Low*	Low*	Low*	SOA	Hi	Hi	Hi	Hi

*Requires complexity on control element

Preferred Approach Selection By Element Pairs

Based upon the considerations of Table 3-8, each element pair that will conduct stationkeeping activities was analyzed and evaluated to identify the preferred approach. Table 3-9 summarizes the results of this approach evaluation.

Table 3-9. Stationkeeping Preferred Approach Selection

Element Pair	Preferred Approach	Rationale
EOS-- EOS, Man Tug, RAM, MSS, Satellite, CPS, RNS, OPD, OLS	Autonomous	Close proximity operations, manned elements involved
Tug (Manned)-- Man/Unman Tug, MSS RAM, Satellite, OPD, CPS, RNS, OLS	Autonomous	Close proximity operations, manned elements involved
Tug (Unmanned)-- RAM, Satellite, CPS, RNS, OPD, Unman Tug	Ground Controlled	Close proximity operations, unmanned elements involved
MSS-- Tug, EOS RAM	Autonomous	Close proximity operations, manned elements involved Detached operations
EOS-- Unman Tug	Autonomous/ Ground Control	Close proximity/long range operations Manned elements involved/detached operations
OPD-- CPS, RNS (Man) CPS, RNS (Unman)	Autonomous Ground Control	Close proximity operations Long duration quiescent operations

Design Influences

Based upon the preferred approach selections for stationkeeping the design influences on the potential elements involved are summarized in Table 3-10. Note that they reflect stationkeeping requirements only. For example, independent state vector determination is not listed for the EOS. It was a requirement for rendezvous.

Table 3-10. Stationkeeping Design Influences

Primary Element	Preferred Approach/Design Influence
EOS	Autonomous Stationkeeping Operations Laser scanning radar Video (TV) capability, S-Band omni data links Passive laser reflectors
Tug (Manned)	Autonomous Stationkeeping Operations Laser scanning radar Video (TV) capability, S-Band omni data links Passive laser reflectors
Tug (Unmanned)	Ground Control Stationkeeping Operations Laser scanning radar Video (TV) capability, S-Band omni data links Passive laser reflectors
MSS	Autonomous Stationkeeping Operations Independent state vector determination Target vehicle state vector determination capability Laser scanning radar Video (TV) capability, S-Band omni data links Detached element control capability Passive laser reflectors
CPS/RNS	Autonomous Stationkeeping Operations Laser scanning radar Video (TV) capability, S-Band omni data links Passive laser reflectors
All Other Elements (including RAM)	Autonomous and Ground Control Stationkeeping Target Operations Passive laser reflector, S-Band omni data links

Laser scanning radar is recommended for all active elements for mission safety reasons during close proximity operations except the RAM. The MSS includes the laser for operation in conjunction with detached RAM's. Thus all elements that stationkeep with the RAM have a laser.

Video (TV) was identified as a requirement for stationkeeping solely for inspection purposes. It could be made a kit but basic provisions should be incorporated because of the high frequency of "inspection" operations prior to mating.

Both command and data transfer requirements can be accommodated by S-band omni equipment on the elements. All elements involved in stationkeeping include this type of equipment. In addition all elements that are either controlled or are the target require S-band transponders.

3.4 DETACHED ELEMENT OPERATIONS

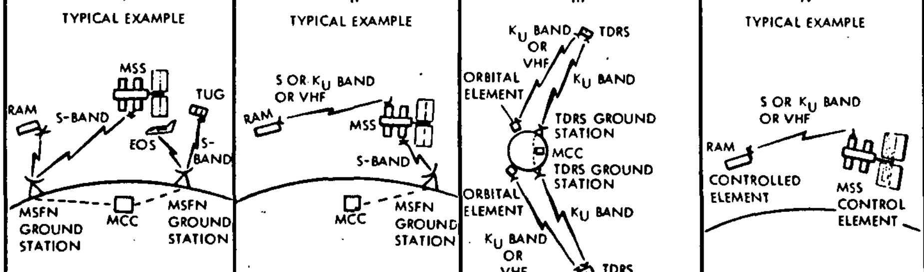
Detached element operations encompass all element-to-element interfacing support necessary to operate a spatial element that is separated from its control center. Either an orbital element or a ground station can be employed as the operational control center.

There is a significant interrelationship between this activity and Communications, Rendezvous, and Stationkeeping. Communications treated the link geometry and hardware concepts for transferring of data. Rendezvous and Stationkeeping were concerned with the generation and use of specific types of data. Detached Element Operations are concerned with the required data transfer rates for space experiment/application operations as well as rendezvous and stationkeeping operations. Communication link constraints are superimposed upon the potential data transfer options.

ALTERNATE APPROACHES

Alternate approaches for detached element operations may be grouped into two major categories: (1) ground operations and control, and (2) space operations and control. Figure 3-6 illustrates these alternatives.

GROUND OPERATIONS AND CONTROL			SPACE OPERATIONS AND CONTROL
I TYPICAL EXAMPLE	II TYPICAL EXAMPLE	III	IV TYPICAL EXAMPLE



	DIRECT FROM GROUND	GROUND TO ELEMENT VIA A RELAY ELEMENT	GROUND TO ELEMENT VIA TDRS	ELEMENT TO ELEMENT
CONSIDERATIONS	LIMITED VIEWING TIME MOST ACCURATE TRACKING/RANGING LIMITED DATA DUMP CAPABILITY	CONTINUOUS VIEWING TIME REDUCED TRACKING/RANGING ACCURACY AT LONGER DISTANCES ADDED RELAY MECHANIZATION REQUIREMENT ADDITIONAL FREQUENCY POSSIBLE RECORD AND DUMP CAPABILITY POSSIBLE INCREASED DATA TRANSMISSION CAPABILITY IN RELAY ELEMENT	ALMOST CONTINUOUS VIEWING TRACKING/RANGING DEGRADED FROM DIRECT BUT PROBABLY SATISFACTORY FOR MOST USES. ADDITIONAL FREQUENCY PROVIDES HIGH DATA RATE CAPABILITY MAXIMUM DATA DUMP CAPABILITY	CONTINUOUS VIEWING REDUCED TRACKING/RANGING ACCURACY AT LONGER RANGES NEED MONITOR OF OPERATIONS AND UPDATE OF TRACKING/RANGING FROM GROUND CONTROL ELEMENT MUST BE MANNED FOR FULL OPERATIONAL CAPABILITY NEED RECORD AND DUMP CAPABILITY NEED ON BOARD DATA PROCESSING

Figure 3-6. Operations and Control Alternatives

Ground Operations and Control

Figure 3-6 illustrates the three communications links that may be used for ground operations and control of the detached elements. Each of the communication link alternates presents certain limitations to full operational support. A combination of links will be required to provide full support. The combination of direct from ground (Link I) and ground to detached element via the TDRS (Link III) can support the operation efficiently. Direct ground to detached element contact is necessary on a regular basis to establish accurate ephemerides of the detached element when a requirement for periodic transfer of large quantities of data exists; the use of the TDRS as a relay element appears attractive to provide a near-continuous communication link. A combination of these links can provide the necessary control and operations of the detached element. Utilization of another orbital space element as a relay imposes additional functional requirements on that element. Such operation is considered necessary for some interfacing activities such as rendezvousing or stationkeeping. In these cases, all communications with the element pair flows from ground through one of the elements.

Space Operations and Control

Space operations and control is implemented by a direct communications space link from one space element to the detached element. Figure 3-6, Link IV, illustrates a typical detached element operation, MSS-to-RAM. All operations support to the RAM is provided by the MSS. In this example, the controlling element requires a manned element to provide full operational capability. Man is necessary to implement the control and operations at the proper time to provide interpretation of received data, to monitor data, and to perform checkout functions. The MSS remains in continuous line of sight with the detached element and thus can easily provide for direct control, reception of data, ranging and tracking, monitoring and checkout of detached element systems, and visual or video inspection. Such support necessitates on-board data processing and displays. One of the considerations is the accuracy of ranging and tracking data in providing accurate ephemerides. The accuracy of the position of the controlling element (MSS, in this example) enters into the detached element position accuracy. For most applications, sufficient tracking/ranging accuracy can be directly provided by the controlling element. Even in this type of operation, it is considered advisable to provide backup and monitoring of operations from the ground.

DESIGN CONCEPT MODELS AND PERFORMANCE CAPABILITIES

Hardware concepts for detached element operations involve the implementation of the communications interface function, the requirement to store, process and transfer large quantities of data to ground and the visual inspection function. Communications design concepts are covered in detail in Volume II, Part 3, Section 1.0, Communications.

Data Transfer to Ground

Table 3-11 summarizes a comparison between data dump and communication capability of (1) element-to-ground direct, and (2) element-to-ground via TDRS.

Table 3-11. TDRS/Ground Network Coverage Comparisons

Parameter	Ground Network (1)		TDRS Network (2)
	Orbits		Orbits
	90°/100 n mi	55°/240 n mi	90°/100 n mi or 55°/240 n mi
Percent of orbit coverage	3.2 percent	10.3 percent	> 90 percent
Maximum gap between contacts	389 min.	435 min.	
Average contact	3.2 min.	6.0 min.	
Data sink capacity/orbit	5.0×10^8 bits	1.7×10^9 bits	$\simeq 2.5 \times 10^{11}$ bits
Line capacity to switching center			
Real time	1.3×10^7 bits/day	4.2×10^7 bits/day	4.0×10^{12}
Post pass (3)	1.5×10^9	1.6×10^9	Not applicable

(1) Goldstone, Madrid, Honeysuckle Creek, Rosman and Fairbanks ground stations per NASA model

(2) Two TDRS satellites, equatorial orbit at 15° and 145°W. Ground station located next to switching center

(3) Assumes recording and dump at ground stations

It is apparent from Table 3-11 that TDRS provides an order of mangitude capability improvement over the ground network. RAM and MSS must use TDRS to provide data transfer imposed by experiments. Other elements must be analyzed to ensure whether such a need, either for continuity or data, is required.

Although TDRS or ground direct may be able to support most missions, an alternate concept is recommended to provide data transfer of large quantities. Use of a recorder with physical recovery of stored data as well as communications data dump can relieve the time usage of the links. Both ground and TDRS must be time-shared among many elements. Provisions should be made for a data recorder with removable stored increments of data on board the space element. These increments can then be transported to ground on regular logistics flights. Recorded data would be that data that does not need real time transfer to ground. Many experiments fall in this category. In many cases, partial data can be transmitted real time and the remainder stored for either later dump or transport.

Data Storage

A trade was performed to define the data storage medium. Two candidates, (1) magnetic tape, and (2) laser recording on metallic-coated mylar film, were analyzed for use. It was determined that magnetic tape recorders with sufficient capacity will be available for orbital operation missions. Present recorders can provide densities of approximately 0.5×10^6 bits per square inch of tape. In the near future (presently in laboratory development), 1×10^6 bits per square inch will be available. These recorders are simple to operate, can provide the necessary life, and will be economically practical.

Visual Inspection

Visual inspection was assumed to be performed using television cameras appropriately placed on the inspecting vehicle. This could be either on a boom or at a docking port with remote control of pointing and focus available to the operator. The inspection operation is supported by the stationkeeping interfacing activity and communication links for remote control and remote viewing when the inspecting element is unmanned.

DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

The operational considerations for each approach are summarized in Table 3-12. The two major considerations are the data rates involved and the required contact time with the data processing center. The detail evaluation is contained in paragraph 4.7 of Volume II, Part 3, Section 4.0.

Table 3-12. Alternate Approach Evaluation

Approaches / Considerations	Direct to Ground Control	Via Space Element	Via TDRS	Space Control	Remarks
Data Handling Capability	1 Mbps	1 Mbps	50 Mbps (a)	1 Mbps	(a) Maximum Ku, 10 Kbps VHF
Communication Contacts	≈10%	100% (b)	≈90%	100% (b)	(b) Assumes LOS between elements and program dump
Operating Frequency	S-Band	S-Band (c)	VHF, Ku	VHF, S-Band	(c) Could use VHF or Ku b between elements
Operational Complexity	Requires preplanned dump schedule or temporary storage	Data dump flexibility via temporary storage	Time share with other elements	On-orbit data reduction or hard storage	
Technology Status	Operational	Operational	Phase B	Phase B	
Orbital Element Design Impact	S-Band omni data storage	S-Band omni data storage	Ku-Band directional	S-Band omni data processing	
C/O & Maintenance	Low	Nominal	Medium (d)	Medium (d)	(d) Ku-band system may require EVA maintenance but computer processing equipment requires more frequent maintenance/ revision
Traffic Model Accommodation	Medium	Low (e)	High	Low (e)	(e) Restricts operational Orbits

One significant conclusion drawn from this evaluation is that a major effort is required to reduce the quantity of data required to be transmitted. This must be accomplished at the source of data generation. There are several techniques of data compression that can be implemented. Perhaps the simplest is a "skimmer" concept that was implemented to reduce the quantity of CSM checkout data that required evaluation. Analyses were conducted to predict the allowable range of values that may occur for a given measurement. Data readouts or transmittals occurred only when these predictions were exceeded.

Preferred Approach Selection by Element Pairs

There are three major orbital activities that are related to the interfacing activity of detached element operations, rendezvous, stationkeeping, and space operations investigation/applications. Rendezvous and stationkeeping approaches and implications were discussed in detail in subsections 3.2 and 3.3. The requirements for space operations are delineated in a previous part of this subsection. All three orbital activities rely upon communication links. Alternate concepts and implications of communication links are presented in detail in subsection 3.1.

An integrated preferred approach is summarized in Table 3-13. The distinction for rendezvous and stationkeeping operations between the alternate approaches is based upon the range between elements and the manning status of the elements involved. The space element relay concept is applicable to unmanned elements operating at close ranges.

Table 3-13. Preferred Approach Selection

Ground Operations and Control					Space Operations and Control	
For Interfacing Activity	I Direct with Ground	II Via a Space Element		III Via TDRS	IV Direct By Space Element	
		Relay	Controlled Element		Control	Controlled Element
Rendezvous & Stationkeeping	EOS, TUG, MSS, CPS, RNS, OLS, OPD, SAT, RAM	TUG CPS RNS	TUG, CPS, RNS, OLS, RAM, SAT, CPS, RNS, OPD OPD OPD	NA	MSS EOS	RAM, TUG RAM, TUG, RNS, OLS, OPD, SAT, CPS
Detached Element Ops	EOS, TUG, MSS, CPS, RNS, OLS, OPD, SAT, RAM	MSS EOS	Detached RAM Attached/ Detached RAM	MSS, SAT, RAM,	MSS-RAM	
Comm Links	S-Band/Omni			Ku-Band Selected SAT's & RAM's	S-Band/Omni Ku-Band Selected RAM's	

Note: Refer to paragraph 4.7 of Volume II, Part 3, Section 4.0, for the detail rationale for this selection.

The paramount conclusion from the analysis of detached operations is the very strong requirement for data compression. Past space programs have been able to operate in conjunction with ground control with respect to data transfer in a dedicated mode. The proliferation of unrelated orbital elements and operations within the next 15 to 20 years will saturate any reasonable ground network. Limitations on measurements and sample rates must become more stringent. Incorporation of techniques that will limit data transfer to only significant deltas from previous readings are highly recommended. Temporary data storage of these increments for future high rate playback (data dump) will become more imperative as space traffic increases. Communication gaps and limited data channels will impose data compression, storage, and high rate playback requirements on almost all orbit stationed elements.

Design Influences

Detached element operations is the prime driver on establishing the communication link design concepts for all elements. In order to comply with the ground network and TDRS models used in this study only VHF, S- and Ku-band transmission frequencies are applicable. Based upon the preferred approaches, by element pair, for this activity as well as Rendezvous and Stationkeeping and the attendant data transfer requirements the recommended data handling characteristics of the various elements are summarized in Table 3-14.

S-band omni communication links are recommended for all elements. Up to 1 Mbps data rates can be accommodated on this link. Selected RAM's and satellites as well as the MSS should incorporate TDRS links. VHF is required to request the use (order wire) of the Ku or high data rate TDRS channel.

It is recommended that a scanning laser radar be incorporated on all the elements involved in detached element operations except RAM's and satellites.

Only the MSS is required to include data processing equipment, because by definition, one of the primary functions of the MSS is to provide an orbital data evaluation facility.

RAM access to both the EOS and MSS communication links is recommended. In the case of the EOS the basic capability is recommended. The MSS is driven to the Ku-band link by the proposed RAM data transfer requirement.

The EOS and MSS both should contain autonomous state vector update, thrust vector maneuver computation, and tracking and ranging capability. Normally, the tug should rely upon either ground control or the MSS for these functions. However, some tug missions will require autonomous operations because of quick response requirements that precluded waiting for ground contacts.

Table 3-14. Detached Element Ops Design Influences

Element	Communication Link	Data Handling Characteristics
EOS	S-band omni Laser	1 Mbps data transfer (TV) 10 kbps (commands) Autonomous state vector update Thrust vector determination Tracking and ranging; S-band and laser RAM access to comm. link Transponder
Tug	S-band omni Laser	1 Mbps data transfer (TV) 10 kbps (commands) Tracking and ranging; laser Transponder
RAM	Nominal: S-band omni Selective: VHF and Ku directional	Up to 10 Mbps (Ku band) 1 kbps order wire (VHF) Up to 1 Mbps data transfer (S-band) Data compression in all cases Data storage up to 15 reels/day Access to comm. links - EOS and MSS Transponder; S and Ku
MSS	S-band omni VHF and Ku band directional Laser	Up to 10 Mbps (Ku band) 1 kbps order wire (VHF) 10 kbps commands (S-band) Up to 10 Mbps (Ku band) Autonomous state vector update Tracking and ranging, S-band and laser RAM access to communication links Data processing, reduction, storage, real time display Transponder
Satellite	Nominal: S-band omni Selective: VHF and Ku band directional	Up to 10 Mbps (Ku band) 1 kbps order wire (VHF) Up to 1 Mbps (S-band) Data compression in all cases Transponder; S and Ku
CPS/RNS	S-band omni Laser	1 Mbps (TV) Tracking and ranging; laser 10 kbps commands 10 kbps data transfer Transponder
OPD	S-band omni Laser	1 Mbps (TV) Tracking and ranging; laser 50 kbps data transfer 10 kbps commands Transponder

INFLUENCES OF INTEGRATED MISSIONS

The primary emphasis in the study of detached element operations was the same as that of the other interfacing activities, space element to element interactions. In addition to the element pair recommendations of the Orbital Operations study, the analyses and conclusions associated with detached element operations also indicated that a subsequent study of integrated missions should be accomplished.

The data management group of interfacing activities developed operational limitations, constraints, hardware recommendations, and nominal operating characteristics of element pair relationships. Only one space element--the MSS--was required to operate with more than one other terminal in the same time frame. MSS could be called upon to communicate with two RAM's, an EOS and/or ground control during the same time period. Frequency multiplex or time multiplex could be used to accommodate this type operation. Other element-to-element data transfer could readily be accommodated with the design concepts proposed.

Although the MSS operation appears complex, examination of the potential multiple links that ground control will be required to accommodate indicates an increase in complexity of at least an order of magnitude. No longer will dedicated link operation be possible. By the 1980's, large numbers of earth orbital satellites--up to 100 by 1990--will be operating simultaneously. In order to ensure effective mission performance for each of these "data producers" a detailed integrated missions analysis needs to be performed. Not only will the "data production" explosion need to be examined, but the logistics for delivery, resupply, and possibly retrieval missions will need careful investigation. Orbital parameters, sensor performance, data contact times, geographical sensor data collection, element compatibility, and other factors must be considered.

An evaluation of the total earth orbital traffic model, considering the factors mentioned above, must be coordinated with an attempt to maximize EOS payload utilization. For example, placement of a maximum number of elements in the same orbit would result in optimum use of the EOS payload capability both for delivery and resupply missions. The definition of the maximum number of elements that could be supported must consider not only the EOS payload capability but also the system capability in terms of the number that can be flown economically, the turn around time, and launch support capabilities. These considerations are all of a physical nature.

A singularly complex operation will be that of the ground collection, processing and distribution of large quantities of data from the multitude of "data producers" in earth orbit. Much of this data will be of real time or near real time interest. Weather, ocean state, and certain earth emergency sensors are examples. Other data from experiment type missions--such as astronomy, solar radiation, and application experiments may not require real time processing. This latter group of data producers needs investigation to determine the most effective way to return data to the ground. Three techniques can be utilized. These are (1) direct real time data dump, (2) onboard data storage and subsequent data dump, and (3) onboard "hard data" storage (either magnetic tape or film) with regular collection and return to ground.

Each of these techniques must be integrated into the total mission model to trade off against contact times with ground network stations or TDRS capability and resupply flights for hard data collection. Contact requirements from three minutes per orbit to 30 minutes per contact and data rates ranging from 20 kbps to 100 or 200 Mbps are anticipated. In addition to the satellites there are manned elements and unmanned elements that must also be considered in establishing the data flow to and through ground control. A total mission timeline needs to be developed to coordinate scheduling of the TDRS, ground network, and the hard data return.

Present operation with the TDRS is limited by the system capability--40 low data rate users and 4 high data rate users at one time. A high percentage of contact time per orbit is available from the TDRS. It is 90 percent or better and is increased as higher orbits are used. Acquisition and tracking of orbital elements and the criteria for time of acquisition, for handover from one TDRS to the other, the scheduling of contacts and the technique for ordering link acquisition must be considered.

Ground network operations have many of the same problems plus the addition of a few more constraints. Besides the limited data capacity and low contact times per station, the ground antennas must slew from one element to another at higher rates and over greater angular ranges than TDRS antennas. TDRS VHF antennas cover the whole orbital spread with no tracking. TDRS Ku antennas have a beamwidth of approximately one degree (3 db points) but at its approximately 20,000 nautical mile distance from low earth orbits, it subtends a minimum of approximately a 350 nautical mile orbital path. An 85-foot (S-band) ground antenna, however, has a beamwidth of less than 0.5 degree and subtends less than 5 miles of orbit at 500 nautical mile altitude. Thus, it must track an element continuously for the duration of the contact. This limits its usefulness in the number of satellites it can support in sequential coverage.

Another major constraint of the ground network is the real time limitation of the station to control center or user communication link of 72 kbps. This necessitates the implementation of ground station high data rate recording and then data dump at the 72 kbps rate or physical transportation of data. Five minutes of 1 Mbps recording would take 70 minutes of dump at 72 kbps. If a number of satellites were contacted in sequence, the data dump capability would soon be saturated. Only 20 satellites per day (or 20 passes per day) recording 5 minutes of 1 Mbps each, would saturate the ground link to the control center. Thus, other methods of data transfer to the control center will need to be implemented.

Acquisition of the desired element, maximum use of data channels, prescheduling of contact with the multitude of orbital elements, handover from one station to the next (either TDRS or ground network), optimization of orbital characteristics, and logistics flight coordination all are indicated as major considerations that should be included in a subsequent integrated missions analysis study.

SECTION 4. SUPPORT OPERATIONS ACTIVITY GROUP ACTIVITY

This section is an extraction and condensation of the significant results from the following five interfacing activities:

- o CREW TRANSFER
- o CARGO TRANSFER
- o PROPELLANT TRANSFER
- o ATTACHED ELEMENT OPERATIONS
- o ATTACHED ELEMENT TRANSPORT

The detail trades and analyses for each of the above interfacing activities are contained in Volume II Part 4 supplemented by Appendix A and Appendix B.

Topics will be used to convey the pertinent study results:

- Alternate Approaches
- Design Concepts
- Preferred Approach Selection
- Design Influences

A separate detailed propellant transfer analysis was conducted and documented in Appendix A9. The significant results from this analysis has been incorporated in the Propellant Transfer interfacing activity report (Volume II Part 4 Section 3.0) and summarized in the Propellant Transfer paragraph (4.3) of this report.

An independent assessment of docking and structural loads for Attached Element Transport is also contained in Appendix A8. The results of this assessment are summarized in the Attached Element Transport paragraph (4.4) of this report.

Two separate detailed analyses were prepared to support Attached Element Operations and are documented in Appendix A6 and Appendix A7.

SUPPORT OPERATIONS GROUP SUMMARY

DESIGN INFLUENCES	DRIVERS	
	PRIMARY	SECONDARY
SHIRTSLEEVE CREW AND CARGO TRANSFER • 41-IN. DIA HATCH • MONITOR ATMOSPHERE • VIEW INTERIOR } ALL EXCEPT NON-MANNABLE ELEM'S • SAT MANIPULATION • EOS AIRLOCK KIT	CREW TRANSFER CARGO TRANSFER	ATTACHED ELEM OPERATIONS MATING EOS PAYLOAD DEPLOY & RETRACT
MANUAL PLUMBED FLUID TRANSFER (SMALL) • 48-IN. DIA CREW WORK SPACE - ALL EXCEPT SAT & UNMANNED TUG AUTOMATIC FLUID TRANSFER	CARGO TRANSFER	--
DIRECT FLUID TRANSFER (LARGE) • RESUPPLY TANK • LINEAR ACCELERATION • STATIONKEEPING EOS } IN PLANE BURN • NO TRANSPORT TUG • NO OPD	PROPELLENT XFER	STATIONKEEPING
RAM SUPPORT (ATTACHED) • LIMITED - EOS • ALL INCLUSIVE - MSS	ATTACH. ELEMENT OPERATIONS	COMMUNICATIONS DETACHED ELEM OPERATIONS

Where practical shirtsleeve crew and cargo transfer was preferred. The maximum hatch opening identified was 41 inches. Work space requirements in the inter element volume for electrical and fluid interconnects was identified as a 48-inch diameter minimum. Resupply of nonmannable elements could be performed either by use of the manipulator or IVA. The preferred concept for propellant transfer was a free flying propellant logistics module delivered to orbit by the EOS that directly transferred the propellant to the user vehicle (CPS, RNS, TUG). In the case of the MSS it should be designed to support the operations of attached element. EOS support provisions to attached elements should be limited to access to available basic capabilities.

4.1 CREW TRANSFER

The crew transfer activity involves the transferring of personnel from one element into another attached element. This study concentrates specifically on personnel transfer between elements and the interfaces associated with this transfer, but does not pertain to personnel transfer within a singular element unless that element is of modular design.

ALTERNATE APPROACHES

The method of crew transfer between attached orbital elements will vary depending upon the orbital vehicle configurations. Transfer may occur between manned elements, from a manned to an unmanned element, and in pressurized or unpressurized conditions. Normally, unpressurized crew transfer will occur between a manned element and a non-mannable element. Exceptions include emergency conditions when crew transfer must be accomplished subsequent to element pressurization failure. Therefore, capability for transferring crew members

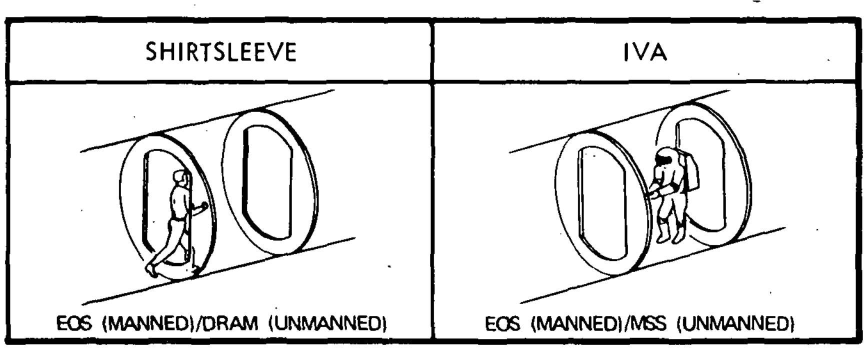


Figure 4-1. Crew Transfer Alternate Approaches

between unpressurized elements must be provided in the design of any crew transfer method.

Figure 4-1 illustrates the basic approaches for normal crew transfer operations.

The selection of one of the two methods to accomplish crew transfer between attached elements is directly related to the configuration of the elements. Shirtsleeve transfer occurs between pressurized vehicles, wherein crew members may maneuver without encumberances of space suits and pressurizing umbilicals. Crew transfer between attached elements, at least one of which is unpressurized, will require crewmen to wear space suits. Crew transfer between attached orbital elements may be accomplished through internal modes and in emergency conditions through external modes.

Internal crew transfer in null gravity can be based on one or both of two concepts: (1) provide a substitute for traction to permit "walking" or (2) accept push-off or pull-along translation. Experimentation using magnetic devices or velcro to restrain the foot for walking has shown that these techniques are unsatisfactory. Push-pull techniques have been utilized in Gemini EVA and Apollo shirtsleeve and EVA activities and are considered the superior method.

DESIGN CONCEPT MODELS

Figure 4-2 illustrates the concept model for shirtsleeve crew transfer.

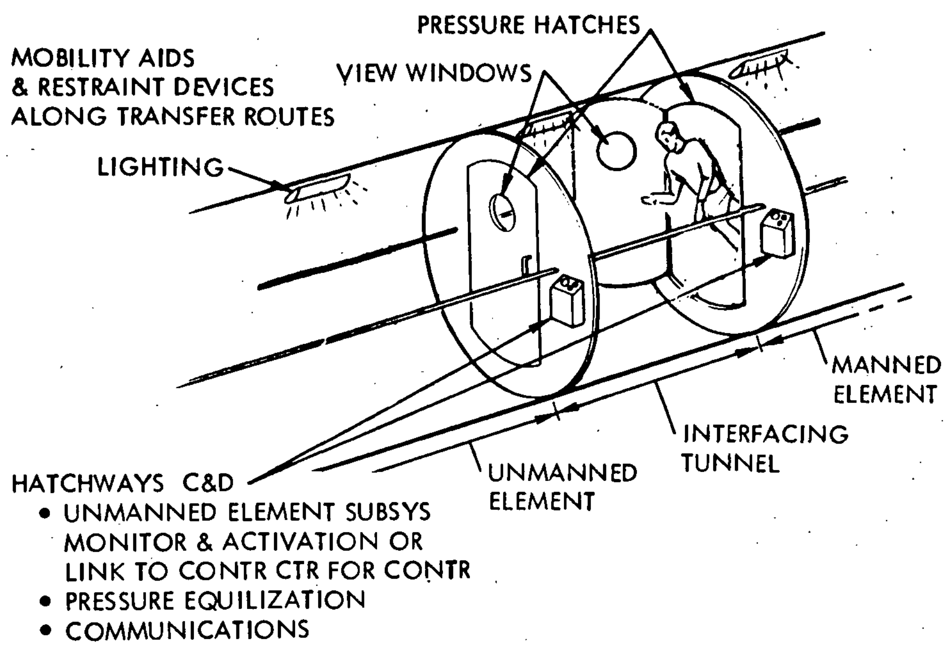


Figure 4-2. Shirtsleeve Crew Transfer Concept Model

Many of the items required for shirtsleeve crew transfer are also required for IVA crew transfer. Figure 4-3 illustrates the complete complement of equipment required for IVA crew transfer.

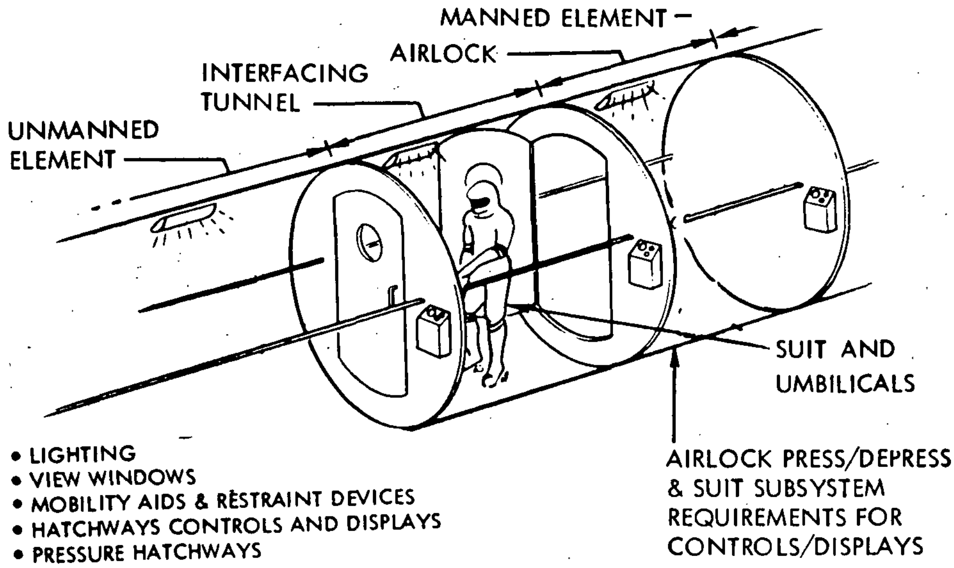


Figure 4-3. IVA Crew Transfer Concept Model

DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

The two crew transfer alternates (shirtsleeve or IVA) were subjected to two separate comparisons. The first comparison evaluated each approach against general design and operational factors. The second comparison applied the results of the first comparison to the various element pairs.

General Design and Operational Comparison

Table 4-1 shows the results of this first comparison. The detail description for each factor is contained in paragraph 1.7 of Volume II, Part 4, Section 1.0.

Table 4-1. General Design and Operational Comparison

Factors	Shirtsleeve	IVA
Technology status	Present	Present
Checkout and maintenance	Low-medium	Medium
Relative cost	Low	High
Safety	Good	Fair
(Additional factors)		
Crew acceptability	Good	Fair
Human effort	Low	High
Weight	Low	High
Mannable elements	Crew rotation/resupply	
Nonmannable elements		Maintenance/replacement
Frequency of trips	Many	Few
Cargo traffic	High	Low
Type of mission	Regularly scheduled	Unique/unscheduled

The predominant criteria used in identifying the preferred approach are: (1) the capability of the elements to sustain life support functions (mannable versus non-mannable), (2) frequency of trips, (3) anticipated cargo traffic and characteristics, and (4) frequency and type of operation to be accomplished upon completion of transfer. Normal crew rotation and cargo resupply, frequent trips, high cargo traffic, and regularly scheduled operations all favor shirtsleeve operations. Shirtsleeve transfer for infrequent maintenance or unique operations in non-mannable elements may be prohibitive.

All crew transfer operations involving crew rotation should be shirtsleeve. All EOS, MSS and CPS/RNS (manned) interfaces are shirtsleeve either because crew rotation occurs, trips are frequent, or the cargo traffic is high.

EOS and Tug crew transfer interfaces with non-mannable elements are all related to maintenance/replenishment operations. In the case of the EOS an IVA/airlock concept is recommended. Since the frequency of these operations is considered to be very low, the airlock could be a cargo bay kit--not a capability of the basic shuttle.

Manned Tug maintenance of non-mannable elements is considered to be even more remote. In the analyses associated with propellant transfer, it was concluded that an OPD was not required. Furthermore, it was established that the EOS can reach the earth parking orbit of the CPS, RNS, or OLS with maximum payloads. Therefore, the only manned Tug maintenance missions are with an unmanned Tug, CPS, or RNS that has become "disabled" beyond the range of the EOS. A more viable approach would be to transport the disabled element with the Tug to be within reach of the EOS.

In the extremely unlikely case that a manned Tug did have to "repair" one of these elements, via crew transfer, it is recommended that the Tug crew compartment serve as the airlock. This mission would be rare and does not warrant either incorporation of an airlock on the basic Tug or development of an airlock "kit" for the Tug.

Preferred Approach Selection by Element Pairs

Table 4-2 summarizes the results of the application of the general and operational comparison to the various element pairs.

Table 4-2. Preferred Approach Selection

Element Pair	Preferred Approach	Rationale
EOS-		
Tug (manned)	Shirtsleeve	Crew rotation
Resupply module (crew)		
MSS		
CPS (manned)		
RNS (manned)		
OLS		
OPD (manned)	Shirtsleeve	
EOS-		
Tug (unmanned)	IVA	Periodic maintenance and unique mission
CPS (unmanned)		
RNS (unmanned)		
OPD		
RAM (nonmannable)	IVA	
RAM (mannable)	Shirtsleeve	Frequent trips, cargo traffic
Tug (Manned)-		
Tug (manned)	Shirtsleeve	Crew rotation
Resupply module (crew)		
MSS		
CPS (manned)		
RNS (manned)		
OLS (manned)		
OPD (manned)		
Resupply module (cargo)	Shirtsleeve	Frequent trips, cargo traffic
Tug (Manned)-		
Tug (unmanned)	IVA(1)	Periodic maintenance and unique mission
CPS (unmanned)		
RNS (unmanned)		
OLS (unmanned)		
OPD (unmanned)		
MSS-		
RAM	Shirtsleeve	Frequent trips, large quantities of cargo
Resupply module (cargo)		
Resupply module (crew)	Shirtsleeve	Crew rotation
CPS/RNS (Manned)-		
Resupply module (crew)	Shirtsleeve	Crew rotation
Resupply module (cargo)	Shirtsleeve	Frequent trips, cargo traffic

(1) Airlock not recommended; see text for rationale.

Design Influences

Table 4-3 summarizes the more significant design influences resulting from the preferred approach selections. Note that monitor, sensors and viewports are rquired for verification of the habitability of an element prior to crew transfer. The hatch size was based upon the minimum required clearance for passage of a crewman in currently defined pressure suits.

Table 4-3. Design Influences

Hardware	Element Applicability
Airlock	EOS only (kit installation)
Habitable environment monitor	EOS, MSS, Tug, CPS, RNS, OLS
Environment sensors	MSS, RAM, Tug, CPS, RNS, Resupply modules, OLS
Docking port view window	EOS, Tug, RAM, MSS, CPS, RNS, Resupply modules, OLS
Minimum 30-inch hatch(1)	All elements
(1)Cargo transfer requires 41-inch hatch (Refer to 4.2)	

4.2 CARGO TRANSFER

The cargo transfer interfacing activity encompasses the operations associated with the transfer of packaged resupply and cargo items, and fluids, between elements. Transfer of large quantities of propellants to storage depots or propulsive elements is defined as the propellant transfer activity and is not included under cargo transfer.

ALTERNATE APPROACHES

The cargo transfer activity is essentially divided into two subactivities which are (1) bulk cargo transfer and (2) fluid cargo transfer. The three alternate approaches for packaged cargo transfer are (1) manual-unaided, (2) manual-aided, and (3) automated. The three alternate approaches for fluid cargo transfer are (1) manual-temporary, (2) manual-plumbed, and (3) automatic-plumbed. All six of these approaches are considered in conjunction with shirtsleeve and IVA crew operational modes.

Bulk Cargo Transfer

As in any land-based cargo transfer method, transfer of bulk cargo between elements could range from purely manual to full automatic. The absence of gravity in the space environment will dictate application of unique transfer and handling requirements to achieve capability throughout the manual to automatic spectrum. Three alternate approaches for bulk cargo transfer between elements are illustrated by Figure 4-4.

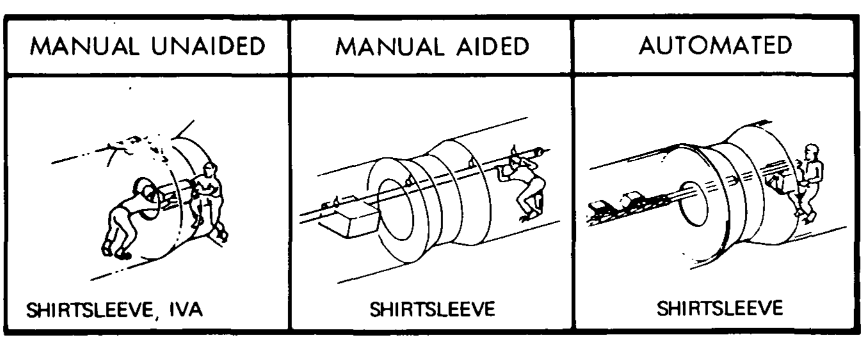


Figure 4-4. Bulk Cargo Transfer Alternate Approaches

Manual-Unaided

This method of cargo transfer relies upon the individual crewman and his capability to handle cargo items without mechanical aids. This capability is applicable to a crewman in either a shirtsleeve, IVA (pressurized spacesuit - umbilical) or EVA (pressurized spacesuit - backpack). During the IVA and EVA modes, additional constraints are imposed by the pressurized spacesuit, which will further limit the crewman's ability to perform useful work. Devices and mechanisms such as tethers, straps, handles, and spacesuit restraints are applicable to this approach. They assist the crewman in his maneuvers but do not directly aid the transfer of the cargo.

Manual-Aided

This category of cargo transfer methods employs mechanical devices for actual transfer functions with the crewman essentially performing control and operator tasks. Through the use of mechanical devices, the greatest diverse capability exists for transfer of cargo between elements. Mechanisms to aid transfer of cargo items include rails for guiding cargo, tethers and cables for propelling and restraining items, manipulators, and manual conveyors.

Automatic

The automatic approach utilizes a mechanization such as a telescoping boom to actually transfer the cargo across the interface. Normally, the manual tasks of loading and unloading the cargo at the terminal ends of the transfer are still required.

A fully automatic approach could be used for cargo transfer between manned and unmanned elements. This approach would be applicable for the resupply and servicing of unmanned elements that cannot accommodate a manned interface other than by means of EVA. A plug-in resupply package could be extended on a telescopic boom to serviceable elements such as satellites or small RAM's that cannot accommodate a docking/airlock interface.

Fluid Cargo Transfer

As stated previously, transfer of fluids across the interface in containers is included in bulk transfer. Fluid flow across the interface requires unique considerations and obviously different approaches. The approaches are: (1) manual-temporary, (2) manual-plumbed, and (3) automatic-plumbed, and are illustrated in Figure 4-5.

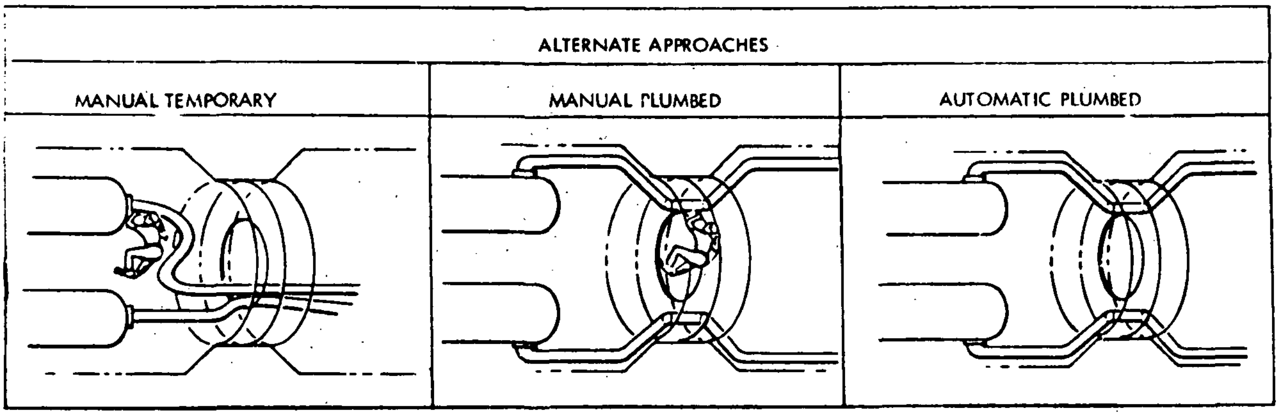


Figure 4-5. Fluid Cargo Transfer Alternate Approaches

Manual Temporary

This approach requires crewmen to manually install and connect lines, pipes, hoses, etc., across the element-to-element interfaces to accommodate the fluid transfer. The installation could be shirtsleeve or IVA.

Manual Plumbed

Plumbed lines are incorporated in the utilities collar of the mating interface and are manually connected upon completion of the mating activity. These lines and connectors are considered as being isolatable from the habitable compartment.

Automatic Plumbed

Plumbed lines are incorporated in the utilities collar of the mating interface and are automatically connected upon completion of the mating activity. This approach would be especially applicable for resupply of fluids to unmanned vehicles that will not accommodate a manned interface through an airlock.

DESIGN CONCEPT MODELS

Design concepts will, of course, vary with each type of transfer. The design concepts are impacted by the procedural assumptions, operations, or requirements. Design concept models were developed to implement each approach. Figure 4-6 describes the manual unaided approach (shirtsleeve) and its associated hardware. If the manual unaided approach were by IVA the design model would be as shown in Figure 4-7.

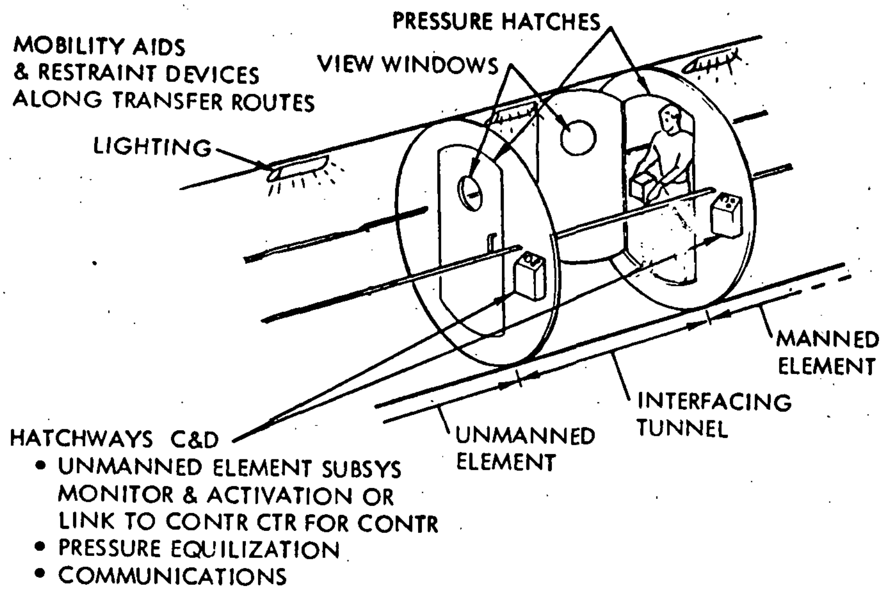


Figure 4-6. Manual Unaided Concept Model

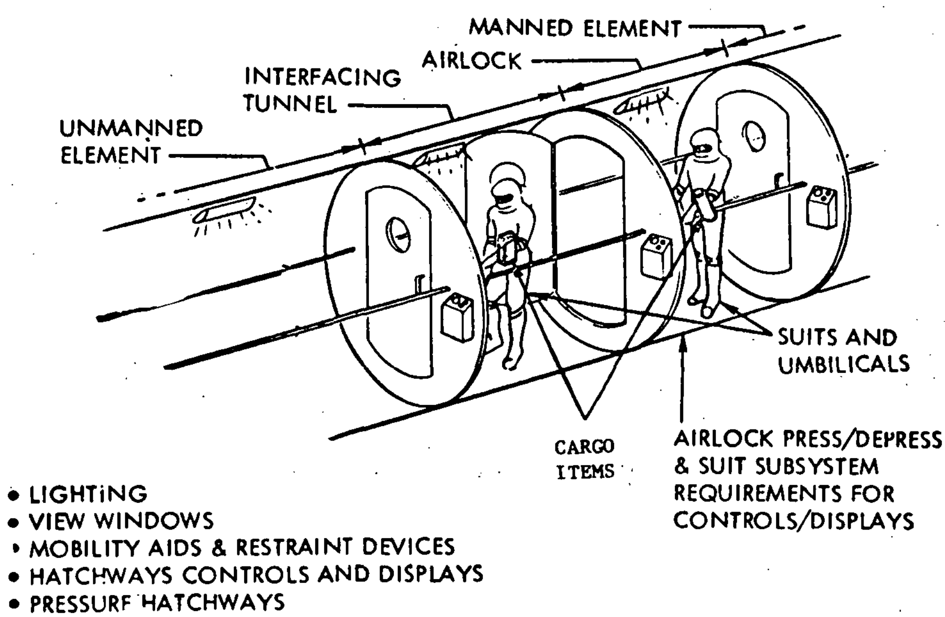


Figure 4-7. IVA Concept Model

The design concept model selected for the manual aided approach utilizes the guiderail transfer system. This model is shown in Figure 4-8. The model more effectively accommodates large-sized packages which are a main driver for selection of this approach.

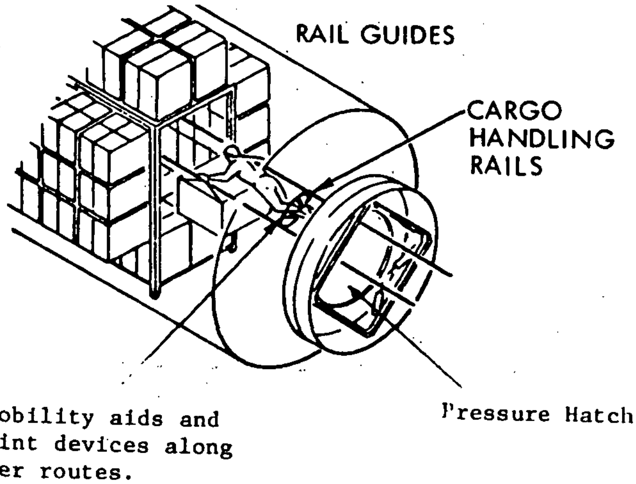
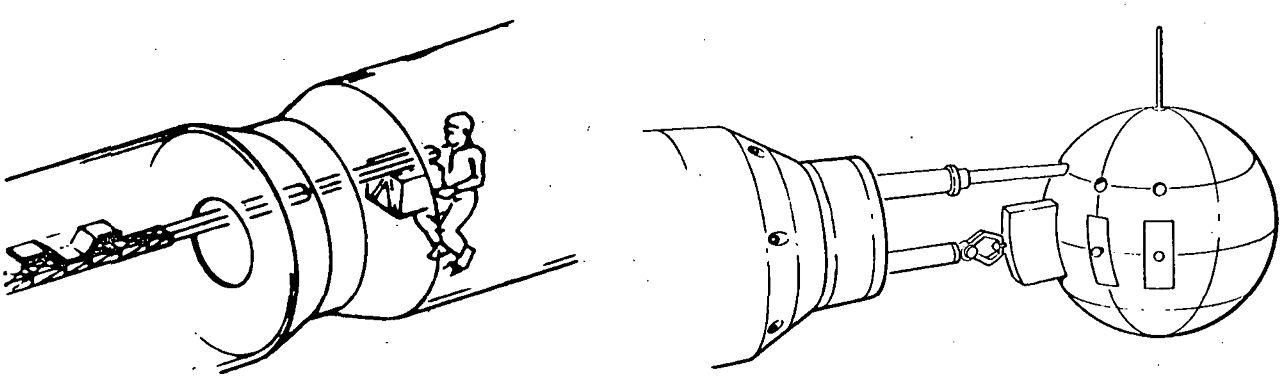


Figure 4-8. Manual Aided Design Model

Two automatic packaged cargo transfer design concept models must be considered. The first is one in which the man is performing loading and/or unloading operations and then activates the transfer system. This is shown in Figure 4-9(a). The second is where the man only controls the transfer system and has no manual participation in the cargo loading and unloading. A good example of this would be a satellite resupply with a manipulator. Figure 4-9(b) shows this concept.



(a) Manual Loading

(b) No Manual Loading

Figure 4-9. Automated Design Models

DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

Each of the two subactivities, (1) Bulk Cargo Transfer and (2) Fluid Cargo Transfer, was evaluated against a set of comparison factors. The results of this evaluation was then applied to the element pairs resulting in the preferred approach selection for each element.

Bulk Cargo Transfer

Table 4-4 summarizes the results of a comparison between the three alternate approaches for bulk cargo transfer. A detailed description of each evaluation factor is contained in paragraph 2.7 of Volume II, Part 4, Section 2.0.

Table 4-4. Bulk Cargo Transfer Approach Comparison

Comparison Factors	Manual Unaided	Manual Aided	Automated
TECHNOLOGY STATUS	Present	Present	Present
CHECKOUT AND MAINT.	Maintenance free, minimum checkout	Some	Specialized maintenance; checkout req'd; redundant method required
COMMONALITY			
Accommodating to crew transfer	Good	Good	Poor
Adaptability/sensitivity	Good	Fair	Fair
RELATIVE COST	Low	Medium	High
SAFETY			
Transfer in hazardous environ. (unpress., high radiation)	Poor	Poor	Good
Normal environment	Good	Good	Good
ADDITIONAL FACTORS			
Electrical power	Not required	Not required	Required
Reliability	High	Medium	Low
Cargo control	Positive	Variable	Positive
Mobility range	Wide	Restricted	Restricted
Operational complexity	Simple	Complex	Simple
Weight	Low	Medium	High
Human effort	High	Medium	Low
Cargo size accom.	Small	Large	Large
Two-way simultaneous transfer	Yes	Requires parallel sys.	Requires parallel system
Interface obstruction	No	Yes	Yes
Speed of transfer	Low	Medium	High

The predominant factors governing the preferred approach selection for bulk Cargo Transfer are cargo size, quantity to be transferred, travel distance, and the available crew mode. The analyses indicated that an automated system was unwarranted except in the case of satellites. The potential resupply items varied from small hand held items to a Control Moment Gyro (CMG). The CMG replacement for the MSS requires a clearance of 38 inches. An additional 3-inch clearance was arbitrarily added to arrive at the maximum hatch opening requirement of 41 inches in diameter. (Crew transfer minimum was 30 inches.) All docking concepts evaluated can accommodate a hatch opening of this size.

The inclusion of resupply modules in the space program directly affects the selections. It is assumed that this element will be used to resupply orbital facilities such as the MSS, OPD, CPS, RNS, and OLS. Thus, the cargo transfer interface between these facilities and the logistics vehicles is simplified. Tug cargo transfer interfaces are reduced only to replenishment of their own consumables. The anticipated cargo transfer from the resupply module to user elements (except the Tug) will be of significant size and quantity that a manually aided concept is recommended for the resupply element pairs. All other transfers can be handed manually unaided.

Automated interchange between unmanned elements and with some satellites will be required. However, these operations will be very infrequent and the device(s) should be a kit installation on the logistics vehicle. Fluid transfer to satellites and between unmanned elements are also very infrequent operations. Automatic provisions for this function should also be a kit installation on the logistics vehicles.

Table 4-5 summarizes the preferred Bulk Cargo Transfer approach for the study elements.

Table 4-5. Bulk Cargo Transfer Preferred Approach Slection

Approach	Applicable Element Interfaces
Manual unaided	All EOS interfaces except some satellites* All Tug interfaces except some satellites*
Manual aided	MSS internal MSS - RAM's MSS - Resupply modules OLS - Resupply modules OLS internal Some satellite interfaces*
Automated	Some satellite interfaces*
*Preferred approach is dependent upon satellite configuration	

Fluid Cargo Transfer

Table 4-6 summarizes the results of a comparison between the three alternate approaches for fluid cargo transfer. A detailed description of each evaluation factor is contained in paragraph 2.7 of Volume II, Part 4, Section 2.0.

Table 4-6. Fluid Transfer Approach Comparison

Comparison Factors	Manual Temporary Interconnect	Manual Plumbed Interconnect	Automatic Plumbed Interconnect
TECHNOLOGY STATUS	Present	Present	Advanced
RELATIVE COST	Medium	Medium	High
CHECKOUT & MAINT.	Low	Low	High
COMMONALITY/FLEXIBILITY	Good	Acceptable	Poor
SAFETY			
Use in hazardous environ.	Poor	Acceptable	Good
Interface obstruction	Poor	Good	Good
Hazardous fluids	Bad	Good	Good
ADDITIONAL FACTORS			
Human effort	High	Low	None

The temporary manual plumbed concept for fluid transfer is undesirable. In this approach, fluid transfer lines occupy crew transfer space, the lines are exposed to damage from either cargo or crew, emergency separation is not feasible, and procedures are complex. Automatic plumbed, though feasible, is complex and costly, limits flexibility, and requires more complex maintenance. Therefore, the preferred approach for fluid transfer was manual plumbed where feasible. Manual plumbed was not feasible in some satellite interfaces and obviously between two unmanned elements.

Figure 4-10 illustrates a concept for manual plumbed interconnect. Adequate space between the pressure bulkheads of mated vehicles (assuming one of the four docking concepts evaluated in this study is used) is available for installation of this concept. The rigid lines on both elements can be outside the pressure shell of both elements. These lines are terminated in valves and connectors between the end hatch of a module and the docking port mating interface. A coupling is manually installed between the two stubbed lines for fluid transfer. A pressure cover is installed over the interconnection.

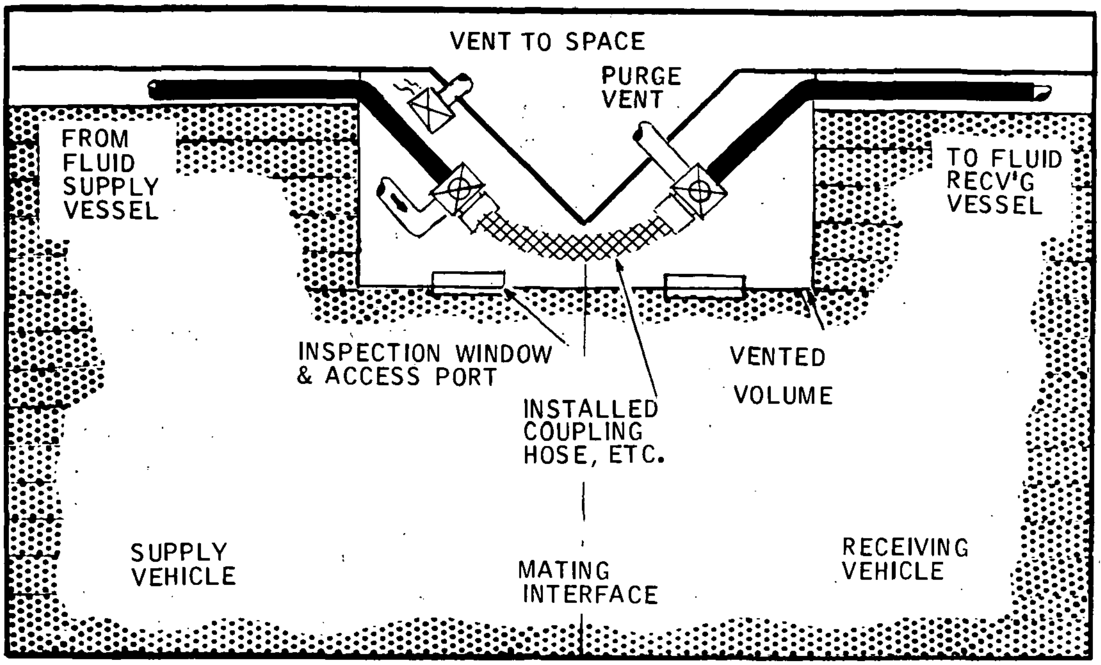


Figure 4-10. Manual Plumbed Fluid Connection

Table 4-7 summarizes the preferred fluid transfer approach for the study elements.

Table 4-7. Fluid Transfer Preferred Approach Selection

Approach	Applicable Element Interfaces
Manual temporary	None
Manual plumbed	All EOS interfaces except some satellites[1] All MSS interfaces All manned Tug interfaces except some satellites[1] All resupply modules[2] All OLS interfaces Some satellite interfaces[1]
Automated	Some EOS-satellite interfaces[1] All unmanned Tug to unmanned element interfaces Some Tug to satellite interfaces[1] Some satellite interfaces[1]

[1]Satellite interface preferred approach is dependent upon the satellite configuration and the bulk cargo transfer concept.

[2]Does not include propellant resupply modules which are automated dedicated interconnects.

Design Influences

Except for satellite and unmanned-to-unmanned element interfaces the impact on the various elements to accommodate bulk cargo transfer is minimal. Manual-aided provisions should be included in the MSS, OLS, RAM and resupply modules. All other transfers can be handled manual unaided. The maximum identified cargo size requires a 41-inch opening (3-inch clearance).

Automated interchanges between unmanned elements and with some satellites will be required. However, these operations will be very infrequent and the device(s) could be a kit installation on the logistics vehicle.

Fluid transfer to satellites and between unmanned elements are also very infrequent operations. Automatic provisions for this function should be a kit installation on the logistics vehicles.

The manual-plumbed concept is a significant design influence on all elements and their docking concept. In the mating activity it was pointed out that a common docking concept was feasible. Similarly, the generic fluid interconnect concept discussed illustrates that commonality across elements is feasible. Future studies on docking optimization/standardization should incorporate a common fluid interconnect concept with at least the operational characteristics of the one developed in this study.

Major design influences are summarized in Table 4-8. All of these requirements are compatible with the Crew Transfer activity. Hatch sizes are based upon the unique cargo transfer requirements. It is quite significant that all four of the docking concepts evaluated in the Mating activity analysis can accommodate the various hatch sizes. It is the utilities interconnect and mating interface that require standardization. Also, those elements that require mechanical aided cargo transfer equipment must have matching hardware interconnects.

Table 4-8. Cargo Transfer Design Influence Summary

Cargo Transfer Requirement	EOS	RAM	TUG	MSS	Rationale	Other Activity Impact
Hatch view windows	X	X	X	X	Viewing of EVA/IVA operations and inspection	Compatible with crew and attached element operations
Interface hatchway controls and displays	X	X	X	X	Habitable environment verification	Compatible with crew and attached element operations
IVA/EVA capability	X (1)		X (2)		Some satellites and RAM's will require EVA/IVA maintenance	Compatible with crew and attached element operations; 30-inch minimum for crew transfer
Manual aided equipment		Some		X	Cargo size and traffic	Requires compatible provisions in mating design concepts
Automatic equipment	X (3)		X (3)		Some satellite servicing requires remote operations	Compatible with mating concepts with satellites
Plumbed fluid interconnect	X	X	X	X	Flexible, safe fluid transfer technique	Gross standardization of utilities interconnections required

(1) Kit installation of airlock
(2) Depressurize crew compartment
(3) Kit installation

4.3 PROPELLANT TRANSFER

The Propellant Transfer interfacing activity pertains to the transfer of large quantities of liquid oxygen and liquid hydrogen propellants in orbit for use by vehicle main propulsion engines. The transfer of relatively small quantities of propellants for attitude control systems, and the transfer of other liquids and gases is included in the Cargo Transfer interfacing activity.

ALTERNATE APPROACHES

The transfer of propellants from an element to the user vehicle in earth orbit can be accomplished in either of two basic ways, (1) fluid transfer or (2) modular transfer. Figure 4-11 shows these two approaches pictorially.

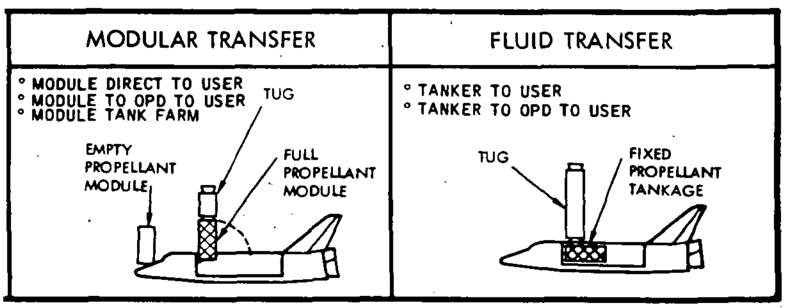


Figure 4-11. Propellant Transfer Alternate Approaches

The modular transfer illustration shows a tug being refueled by an exchange of propellant tanks. This is sometimes referred to as the tank-set concept when the user vehicle does not incorporate permanently attached tanks. The fluid transfer illustration shows a tug being refueled from a propellant logistics tank which remains stowed in the orbiter cargo bay. The fluid transfer approach might also involve the deployment of the logistics tank from the orbiter, followed by the fluid transfer operation. Still another delivery mode might be the separation of the logistics tank from the orbiter, followed by the fluid transfer operation.

As the previous paragraph suggests there are many options or subapproaches for refueling a user vehicle, some of which involve both fluid and modular transfer. In order to identify all potentially viable logistics options for refueling a user vehicle, the sequence block diagram (Figure 4-12) was constructed.

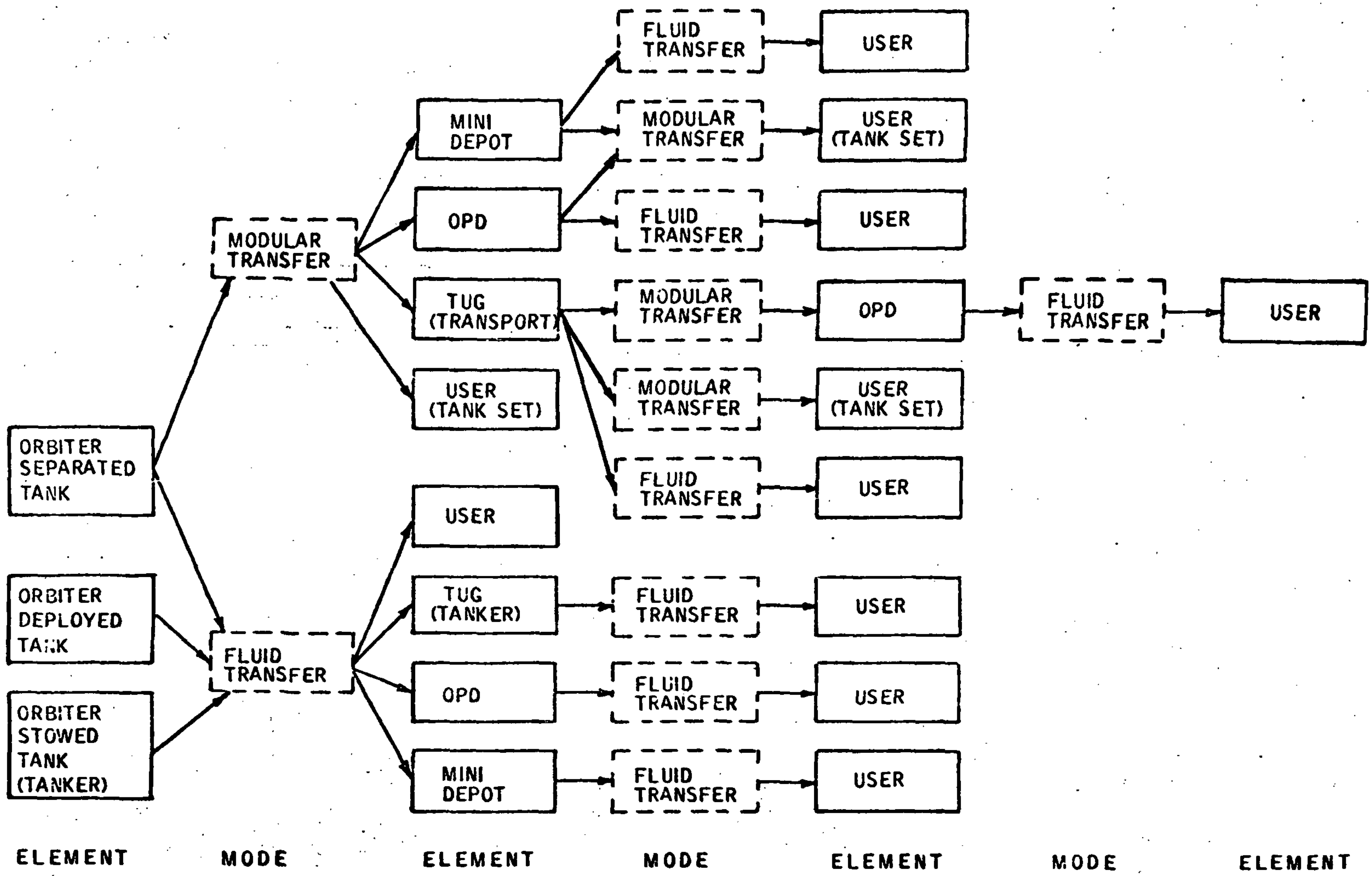


Figure 4-12. Propellant Transfer Logistics Options

The vertical columns of Figure 4-12 alternate between the orbiting element involved and the mode of transfer. For each of the eleven logistics options the sequence starts with the delivery of the propellant logistics tank to earth orbit in the orbiter; and ends with the transfer of propellant to the ultimate user.

Nine of the eleven logistics options include more than one propellant transfer operation. Option No. 4 includes three transfer operations. As can be seen, a modular transfer operation can be followed by either modular or fluid transfer. Fluid transfer is never followed by modular transfer in a given logistics option.

The terms modular and fluid transfer as used herein are defined as:

Modular Transfer. The transfer of a propellant module from one vehicle to another. Modular transfer may be followed by fluid transfer, and may involve the user vehicle tank-set concept.

Fluid Transfer. The transfer of liquid propellant from one tank to another. The receiving tank may be an intermediate orbiting element or an integral (permanently fixed) tank in the user vehicle.

Description of Propellant Transfer Logistic Options

The following is a brief description of each logistics option (Figure 4-12).

Option 1. A logistics tank is delivered to a mini-depot by the orbiter. The orbiter separates from the tank. The user vehicle mates to the mini-depot and is refueled by fluid transfer from the logistics tank which is attached to the mini-depot.

Option 2. A logistics tank (tank set) is delivered to the mini-depot or OPD. The user vehicle (designed for tank set concept) exchanges empty tanks for full tanks at the mini-depot or OPD.

Option 3. A logistics tank is delivered to the OPD. The user vehicle mates with the OPD and is refueled by fluid transfer.

Option 4. A logistics tank is delivered to a tug "transport" by the orbiter. The tug transports the tank to the OPD, where the propellant is transferred by fluid transfer to the user.

Option 5. Similar to Option 4 except that the tug transports the logistics tank (tank set) to the user vehicle (designed to accommodate tank-sets) where the empty user tank is exchanged for a full tank.

Option 6. Similar to Option 4 except that the tug transports the logistics tank to the user which is refueled by fluid transfer.

Option 7. A logistics tank (tank set) is delivered to the user vehicle by the orbiter. The empty tank from the user vehicle (designed to accommodate tank sets) is exchanged for the full tank.

Option 8. A logistics tank is delivered directly to the user, followed by fluid transfer to the user integral tanks.

Option 9. A logistics tank is delivered to a tug "tanker." Fluid transfer takes place to the tug integral tanks. The tug then separates from the logistics tank and flies to the user vehicle, where fluid transfer takes place to the user integral tanks.

Option 10. A logistics tank is delivered to the OPD where fluid transfer occurs. Subsequently fluid transfer occurs to the user vehicle integral tanks.

Option 11. A logistics tank is delivered to the mini-depot where fluid transfer occurs. Subsequently fluid transfer occurs to the user vehicle integral tanks.

Deletion of Propellant Transfer Logistic Options

Although the above defined options are all potentially viable, some are considerably more attractive than others. Due to the large number of options (or sub-approaches) identified, it was deemed desirable to delete the least attractive options from further detailed analyses in the Orbital Operations Study. The results of the deletion are detailed in paragraph 3.3 of Volume II, Part 4, section 3.0 and briefly summarized below.

- Delete Options 4, 5, 6, and 9

  Rationale. An analysis of the role of the Tug as an intermediate delivery vehicle indicates no advantage since the EOS is capable of delivering the propellant directly to the user without a reduction in payload delivery capability.*

- Delete Options 3 and 10

  Rationale. The OPD is never cost effective compared to either additional orbiters or an additional CPS.

- Delete Option 2

  Rationale. Option No. 7 involves only a single transfer operation and does not entail the additional costs of a mini-depot to serve as an intermediate tank holding station. Therefore Option 2 was rejected in favor of Option 7.**

*The potential mode where a CPS returns to an elliptical orbit which is circularized by a tug was not analyzed in this study.

**Two other mini-depot concepts as described under Design Concept Models, were retained for more detailed analyses.

Logistics Options Remaining for Further Study

As a result of the deletion of options 2, 3, 4, 5, 6, 9, and 10, there are four remaining logistics options, i.e., options numbers 1, 7, 8, and 11 (see Figure 4-13). Options Numbers 1 and 11 utilize the mini-depot. Option number 7 only requires that the user vehicle be designed to accommodate tank sets. Options 7 and 8 utilize no intermediate element between the orbiter and the user vehicle other than the propellant logistics tank.

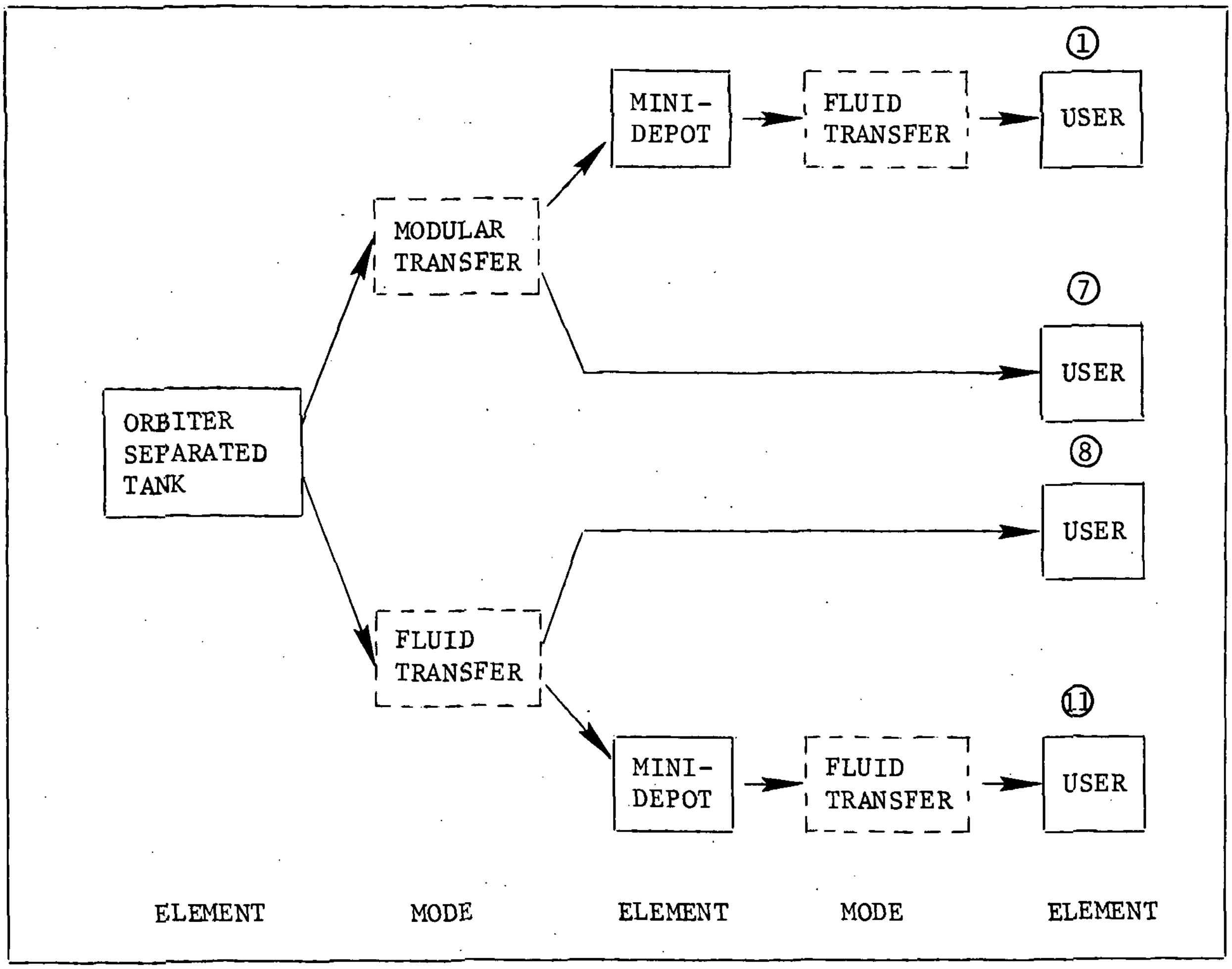


Figure 4-13. Preferred Propellant Transfer Logistic Options

DESIGN CONCEPT MODELS

This paragraph presents sketches and narrative briefly describing design concept models for specific propellant transfer hardware elements. These elements include propellant logistics tanks and mini-depots, and their related subsystems. The intent herein is to present a viable design concept for each element of the four propellant logistics options (Options No. 1, 7, 8, and 11) selected for further study. Design trade studies are involved only to the extent necessary to assure the selection of a viable concept, as opposed to an optimum concept. A detailed presentation of design concepts is included in Appendix A9 in support of the summary data included in this paragraph.

Liquid/Vapor Interface Control

In order to transfer propellant from one element to another (fluid transfer) some means of liquid/vapor interface control must be provided in order to assure transfer of liquid only through the transfer plumbing. This can be accomplished in several ways as illustrated by Figures 4-14, 4-15, and 4-16.

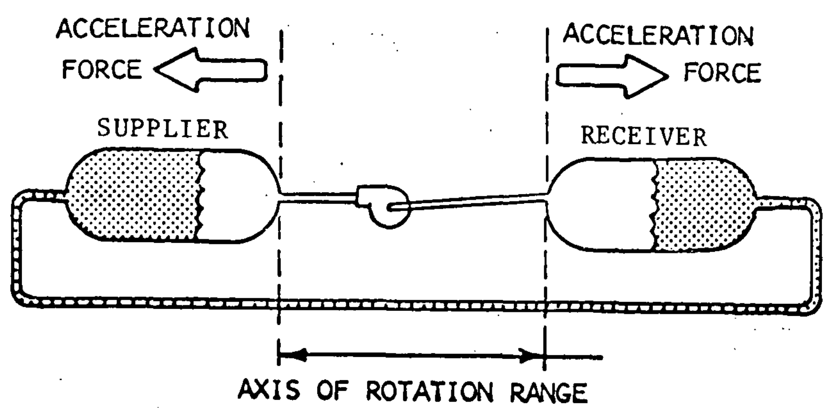


Figure 4-14. Radial Acceleration

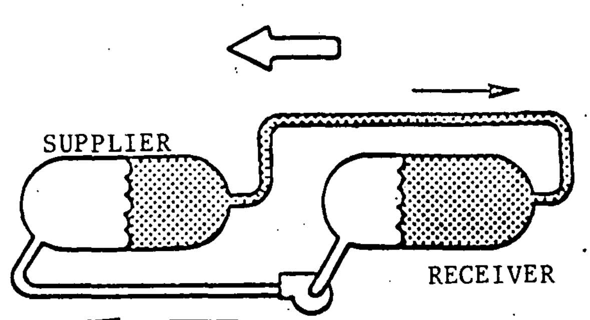


Figure 4-15. Linear Acceleration

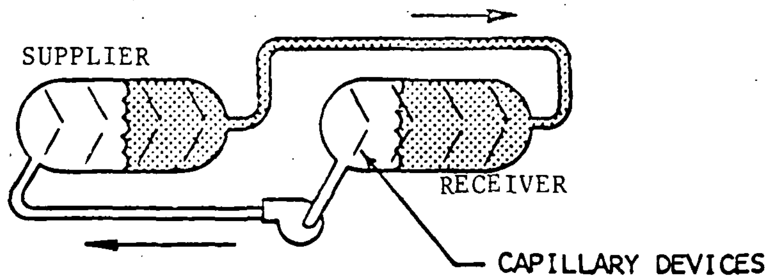


Figure 4-16. Surface Tension

Three concepts shown are (1) radial acceleration, (2) linear acceleration, and (3) capillary action. All three are viable concepts, although capillary action requires more advanced technology in its application.

Radial acceleration requires that the combined c.g. of the attached elements always remain outside of both the supplier and the receiver tanks during transfer. From a physical standpoint this may require a long boom between the supplier tank and the user vehicle. This is particularly true when the user vehicle is a heavy element like the CPS or RNS. The radial acceleration method requires thrusting to establish the desired rotation rate, followed 10 to 15 hours later by another short thrusting period to null out the rotation. During the transfer period, minimal thrusting is required to maintain attitude stability. (Refer to Appendix A9 for further discussion.)

The linear acceleration method requires continuous thrusting during the transfer operation to maintain liquid/ vapor interface control (a period of 10 to 15 hours).

Modular, Linear Mini-Depot

Logistics Option No. 1 utilizes a mini-depot as an intermediate propellant resupply element, involving fluid transfer from the depot to the user vehicle. Linear acceleration has been selected as a viable means of liquid-vapor interface control during propellant transfer to all three user vehicles, i.e., CPS, RNS, and tug. In the case of the CPS and RNS, radial acceleration does not appear desirable at this time due to the large boom length required (see Appendix A9). Figure 4-17 illustrates a mini-depot design concept utilizing linear acceleration for liquid/vapor interface control.

Logistics Option No. 7 involves a modular transfer of a tank-set directly to a user vehicle. This tank would serve a dual purpose, i.e., that of a logistics tank in transit, followed by attachment to the user vehicle where it would become the propellant tank (or tanks) for the main propulsion engines. This logistics option involves an exchange of full for empty tanks at the user vehicle. The fluid transfer interface between this tank and the user engines would be similar to the interface between the logistics tank (described for logistics Option No. 1) and the mini-depot. These similarities and some of the potential differences are discussed in Appendix A9.

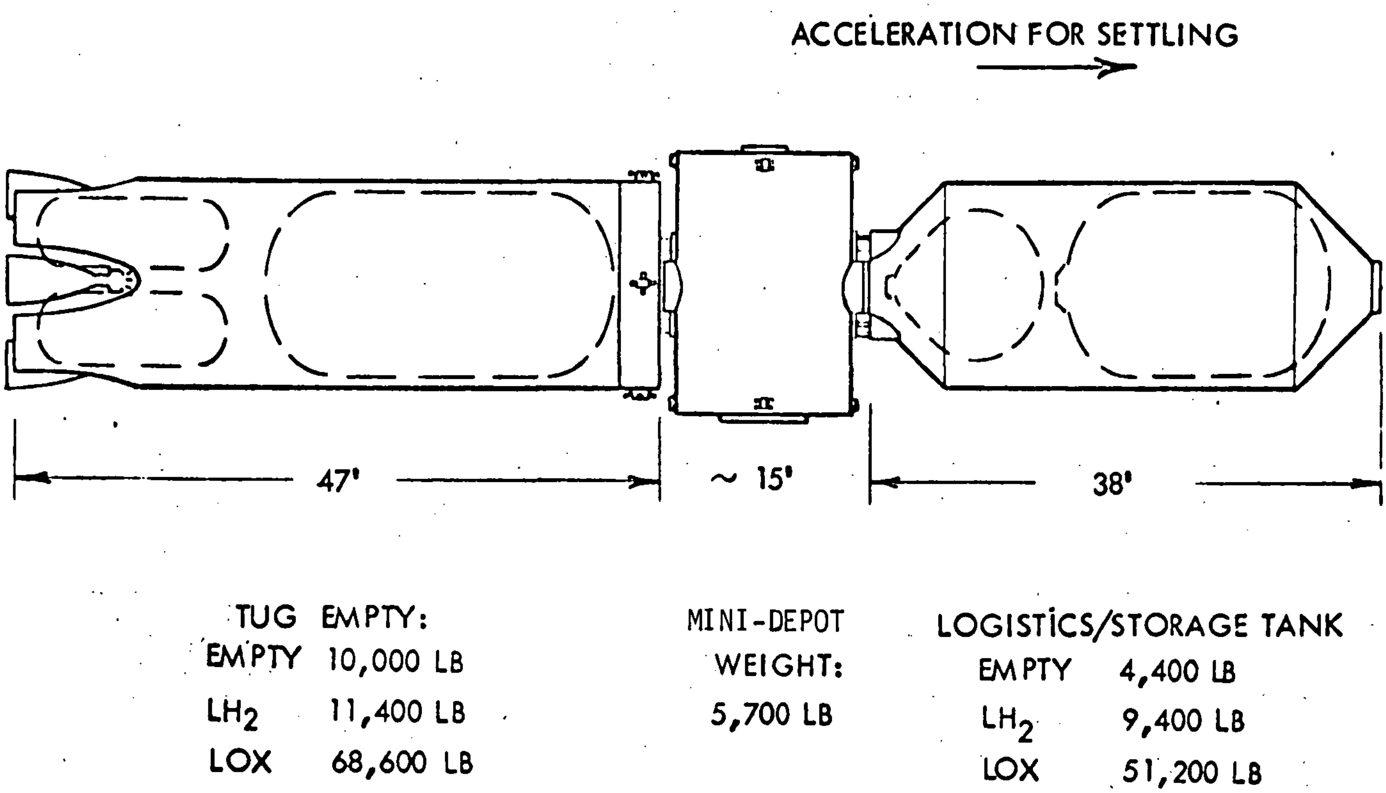
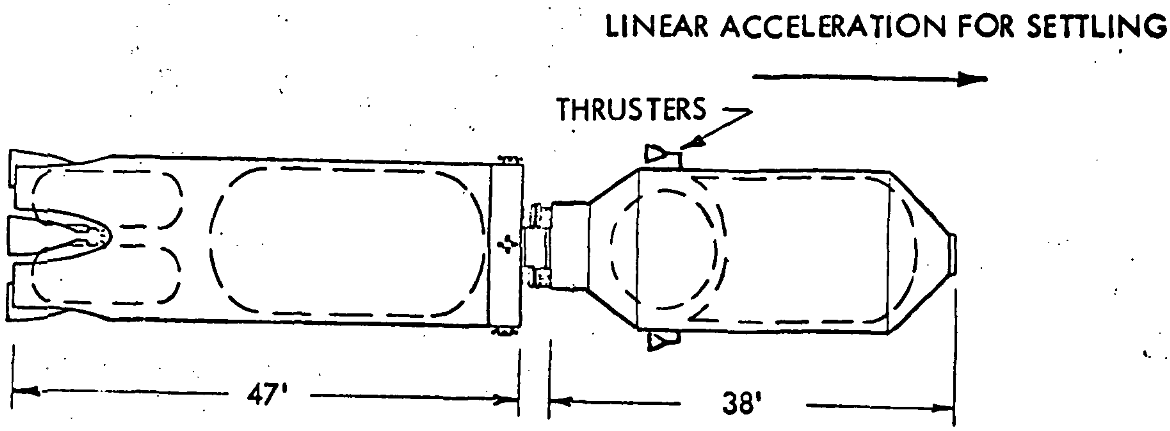


Figure 4-17. Modular, Linear Mini-Depot

Fluid Transfer, Linear Acceleration

Logistics Option No. 8 incorporates a single fluid transfer directly to the user vehicle from the logistics tank delivered by the EOS orbiter. Since no mini-depot is involved, either the user vehicle or the logistics tank must incorporate the propellant transfer compressors, interconnect extension mechanisms, and the thrusters for liquid/vapor interface control. To minimize the weight impact on the user vehicle, these features are incorporated into the logistics tank. Figure 4-18 illustrates this design concept.



TUG		TRANSFER CAPABILITY LOGISTICS TANK	
EMPTY	10,000 LB	EMPTY	4,800 LB
LH_2	11,400 LB	LH_2	9,300 LB
LOX	68,600 LB	LOX	50,900 LB

(Including pumps, ext. mech., etc.)

Figure 4-18. Fluid Transfer, Linear Acceleration

Permanent Tankage, Linear Mini-Depot

Logistics Option No. 11 utilizes the mini-depot as an intermediate propellant resupply element, somewhat similar to the mini-depot described for Logistics Option No. 1. The mini-depot for Option No. 11, however, would have integral tanks requiring fluid transfer into them from a logistics tank, followed by fluid transfer from the mini-depot to the user vehicle. This concept is illustrated in Figure 4-19. The logistics tank used with this concept would be essentially the same as that described for logistics Option No. 1. With this concept, the orbiter could return to earth after the depot is refueled and before the propellant is transferred to the user vehicle.

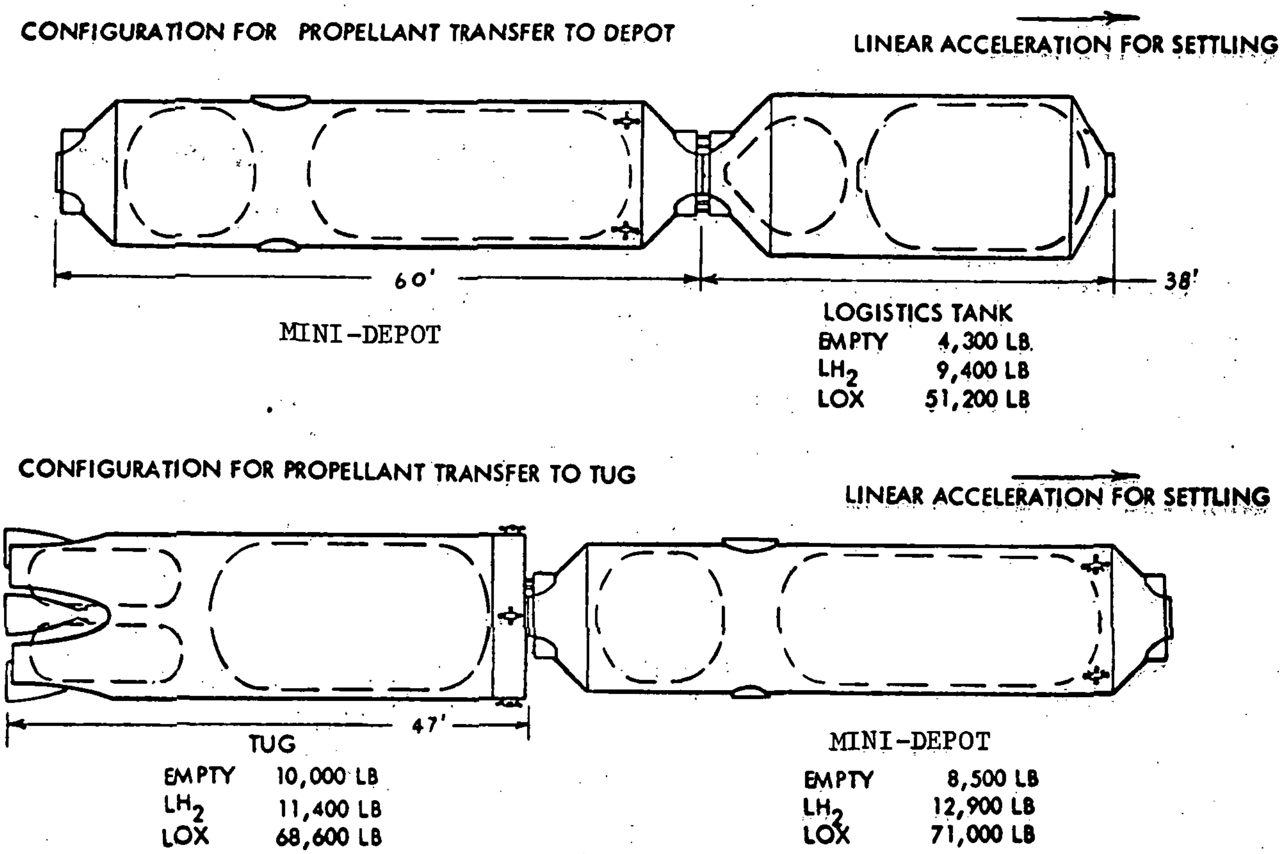


Figure 4-19. Permanent Tankage, Linear Mini-Depot

DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

The selection of the preferred logistics option for refueling each of the user vehicles (RNS, CPS, and tug) is based upon the evaluation of eight factors. One of these factors is the design influence or impact on the user vehicle. The design influence on the user is essentially the same for all options except Option No. 7, the tank-set concept. The design influence of fluid transfer on the user is presented in Paragraph 3.6 of Volume II, Part 4, section 3.0 and in Appendix A9.

Table 4-9 summarizes the penalties on the user vehicle if the modular interchange (tank-set) concept is used.

Table 4-9. Tank-Set Impact on User

User Vehicle Design Configuration	Non-Mod.	Modular	
Vehicle Tank Concept	Perman.	Perman.	Tank-Set
Vehicle Weight Penalty Items:			
- Ground Insulation System			✓
- Additional Handling Require.			✓
- Additional Boiloff Capacity			✓
- Additional Interf. Isol. Equip.		✓	✓
- Additional Struct. for Rigidity		✓	✓
- Additional Docking Port		✓	✓

The use of the fluid transfer mode allows the user vehicle to have tanks which remain permanently attached to the user and which can be delivered to orbit <u>empty</u>. These permanent tanks, as indicated on Table 4-9 can be of two types: (1) tanks which are integral to the basic vehicle design and which would be installed in the vehicle on the ground (non-modular vehicle design); and (2) tanks which are delivered to orbit separately, and assembled permanently to the vehicle cluster in orbit (modular vehicle design). In addition, the modular vehicle design is also amenable to the propellant tank-set concept which involves the exchange of full tanks for empty tanks in earth orbit, i.e., the modular propellant transfer mode.

Table 4-10 presents a comparison of the four options, the rationale for the ratings applied for each evaluation factor, and the final selection of a preferred approach.

Due to the utilization of the mini-depot as an additional element, Options No. 1 and 11 receive relatively unfavorable ratings against the following evaluation factors: safety impact; maintenance impact; relative cost; and operational complexity. From a commonality standpoint Option No. 7 rates lowest because each user vehicle (with the tank-set concept) would require tanks which are optimized for the user vehicle and its mission.

A considerable degree of commonality in tank design for refueling of the Tug and CPS by Options No. 1, 8, and 9 could exist. The external dimensions, docking ports, and much of the internal design of the logistics tanks could be the same. Due to the additional boil-off of LH_2 in the CPS (as compared to the tug) because of the longer time period required to refill a CPS, the ratio of LH_2 to LO_2 in the logistics tank would be higher for the CPS. Since the RNS requires only LH_2, and because the orbiter cargo bay imposes a volume limitation on transport of LH_2, the RNS logistics tank would be approximately 60 feet long. The Tug/CPS logistics tank would be approximately 40 feet long.

Table 4-10. Comparison/Selection of Logistics Options

Evaluation Factor \ Logistics Option	① * MT → M. DEP FT → USER	⑦ MT → USER	⑧ FT → USER	⑪ FT → M. DEP FT → USER	RATIONALE FOR RATINGS
Safety impact	High	Medium	$\boxed{\text{Low}}$	High	Greater impact with additional element
Maintenance impact	High	$\boxed{\text{Low}}$	$\boxed{\text{Low}}$	High	Mini-depot requires additional maintenance
Technology status	Advanced	Advanced	Advanced	Advanced	Technology development approximately equal
Relative cost	High	$\boxed{\text{Low}}$	$\boxed{\text{Low}}$	High	High cost of additional element
Operational complexity	High	Medium	$\boxed{\text{Low}}$	High	High with additional element medium with tank set
Commonality	$\boxed{\text{Medium}}$	Low	$\boxed{\text{Medium}}$	$\boxed{\text{Medium}}$	Low with tank set. Very similar logistics tank for tug and CPS
Design influence on user	$\boxed{\text{Low}}$	High	$\boxed{\text{Low}}$	$\boxed{\text{Low}}$	Integral tanks can minimize weight of user vehicle
Number of orbiter flights:					
Tug	1.36	1.32	1.35	1.38	Option ⑪ losses highest due to two fluid transfers
CPS	19.20	18.10	19.19	20.44	
RNS	9.16	8.90	9.16	9.46	

NOTES:
- $\boxed{}$ Denotes favorable rating
- See Figure 3-19 for logistic options flow chart
- * MT = Modular Transfer; FT = Fluid Transfer

PREFERRED OPTION: No. ⑧ Fluid transfer to user from a logistics tank. The logistics tank is delivered directly to user by orbiter.

RATIONALE FOR SELECTION: Lowest cost and operational complexity. Good commonality and relative low design impact on user

The number of orbiter flights required to refill each of the user vehicles is a minimum with Option No. 7 since the only propellant losses involved are boil-off losses. Option No. 11 requires the most number of orbiter flights primarily because of the propellant losses associated with an additional fluid transfer operation. The supporting data for the determination of the number of flights are documented in Appendix A9.

The preferred logistics option selection for propellant resupply of all user elements is Option 8. The primary drivers are cost and operational complexity. Secondary drivers are commonality and relatively low design impact on the user vehicles.

Desirable Technology Item

Linear acceleration has been selected in this study as a viable concept for liquid/vapor interface control for fluid transfer. The other two identified alternatives are rotational acceleration and capillary devices for surface tension. All three concepts are discussed in Design Concept Models and in Appendix A9. The primary reason for not selecting a capillary concept is the development problems and the associated development risk.
If future development efforts related to capillary concepts should prove this concept feasible, a re-evaluation of its application to fluid transfer might result in the selection of this concept over the other two alternatives.

4.4 ATTACHED ELEMENT OPERATIONS

Attached Element Operations designate that interfacing activity in which one element provides operations support to another attached element while the latter element is stored, operating, or being serviced or checked out. The support may take different forms. It may be as simple as monitoring the attached element while it is in quiescent storage. It may involve removal of exposed film and supply of expendables during periodic servicing; or it may be a provision of some service such as orientation or pointing of the attached element while it is operating. Other examples of operational support considered are pressurization of an attached element to permit crew visitation, data transfer and analysis, supply of electric power, and thermal control.

ALTERNATE APPROACHES

Three alternate approaches were defined for Attached Element Operations: (1) independent, (2) dependent, and (3) modular dependent. Pictorially, the three preferred alternate approaches for Attached Element Operations are illustrated by Figure 4-20.

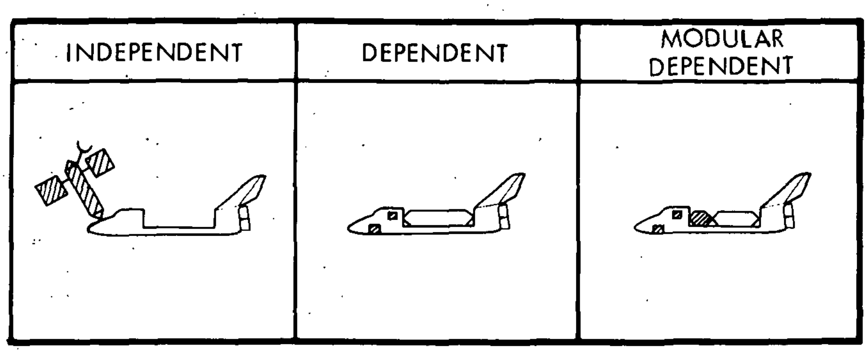


Figure 4-20. Attached Element Operations Approaches

Independent

The independent approach is applicable to those functions that are performed by an element (such as a RAM) completely independent of the attached supporting element (such as an EOS). A typical independent function might be atmospheric temperature control and circulation being provided solely by the RAM.

Dependent

The dependent approach is applicable to those functions where the supported element (such as a RAM) is completely dependent upon the attached supporting element (such as an EOS). An example might be the dependency of the RAM on the EOS for transmission of voice and telemetry data (less than 1 Mbps) from the orbiting pair to ground stations.

Modular Dependent

The modular dependent approach is applicable to those functions that are performed through support obtained from supplemental modules (such as a RAM support module) or kits that are add-on to the basic design configuration of either the supported element (such as a RAM) or the supporting element (such as an EOS). Communications and environmental control provide good examples of this alternate approach. If communications data rates are generated in excess of 1 Mbps and need to be delivered from orbit to ground in real time, then the RAM will need to provide its own processing and transmission by means of add-on equipment. (In conjunction with this equipment, the RAM would utilize the EOS S-band omni antenna and RF distribution components, which is illustrative of the dependent approach.) Environmental control for life support within a payload module will draw upon a separate module for provision of the habitable environmental control support.

DESIGN CONCEPT MODELS

Three design concept models were developed to establish functional requirements capabilities for subsequent evaluation of the alternate approaches. These design concept models are: (1) Modular Space Station, (2) Earth Orbital Shuttle, and (3) Research and Applications Modules.

Modular Space Station Design Concept Model

There are several significant characteristics of the modular space station that will have a direct influence on the alternate approach selection. These characteristics encompass communications, attitude control, thermal, electrical power, crew, environmental control, and orbit maintenance and collectively constitute the MSS design concept model. The MSS itself represents an iterative design process wherein its design is directed by the basic mission objectives; namely, the experiment program objectives. As a result, it is likely that there already exists a strong compatibility between RAM operations and the MSS. However, because objectives of the space program are constantly changing, it is appropriate that there exist a design concept upon which the experiment programs can be evaluated and this is presented below.

Figure 4-21 defines the MSS characteristics that are pertinent to RAM operations.

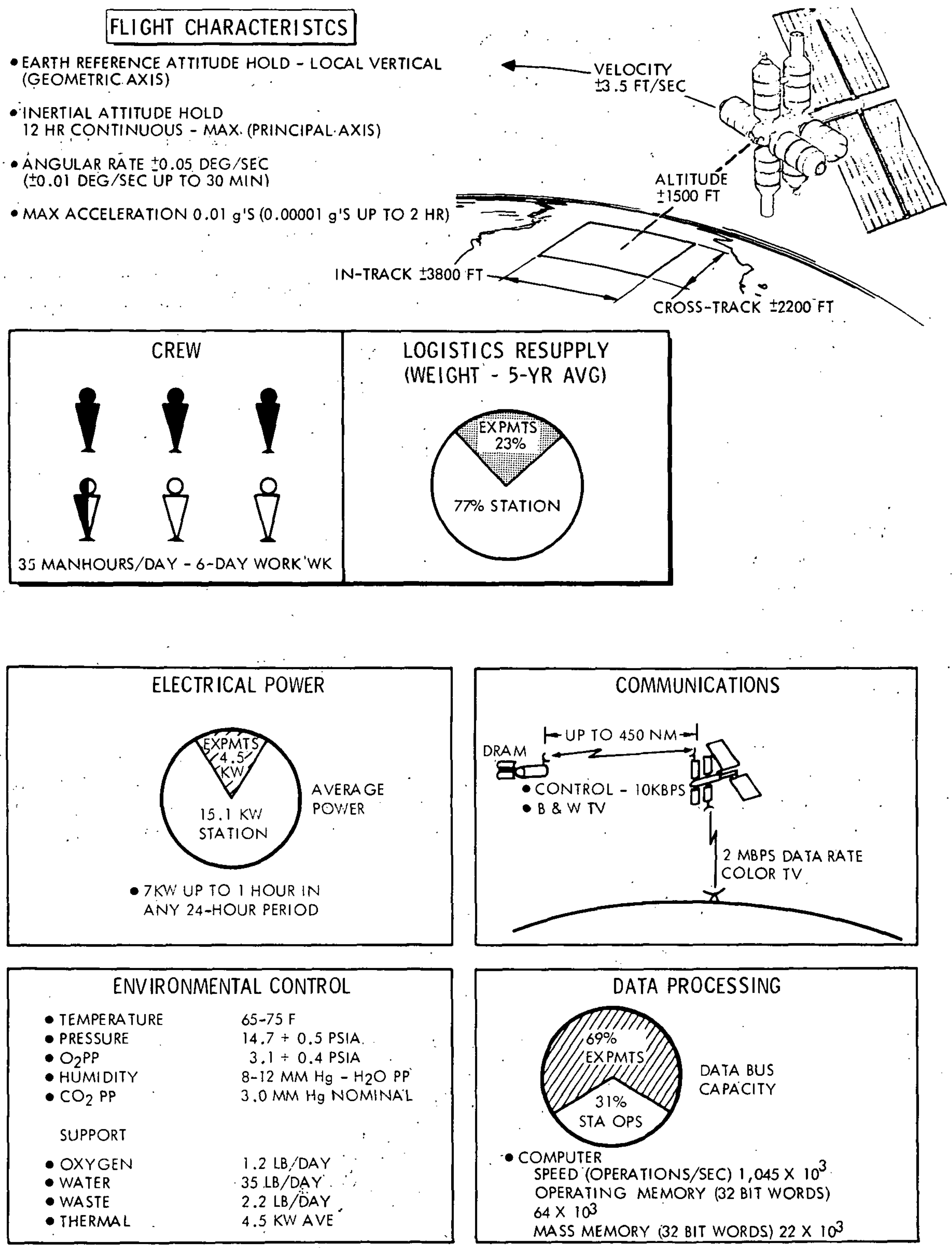


Figure 4-21. MSS Design Concept Model

Earth Orbit Shuttle Design Concept Model

The Earth Orbit Shuttle (EOS), like the MSS, serves as the supporting vehicle during Attached Element Operations and, as a result, a design concept model needs definition in order to proceed with the subsequent analyses of this activity. Table 4-11 defines the EOS interface characteristics and represents the design concept model.

Table 4-11. EOS Design Concept Model

Characteristic	Interface
Electrical power available	
Average	500 watts
Peak	800 watts
Energy	20 kWh
Maximum cargo bay size	15 ft diameter, 60 ft length
Crew provision	28 man-days
Pointing accuracy	±0.5 degree
Stability	±.025 deg
Combined jet	0.05 deg/sec
Single jet	.025 deg/sec
Mission duration	7 days, nominal
Orbit/payload	25,000 lb to 275 n mi x 55 degrees inclination

Communications

The EOS communications interfaces of interest to Attached Element Operations activity are those between EOS/attached RAM s and EOS/ground stations. No communication link presently exists between the EOS and the tracking and data relay satellite (TDRS). Figure 4-22 illustrates the external communications links from EOS to ground.

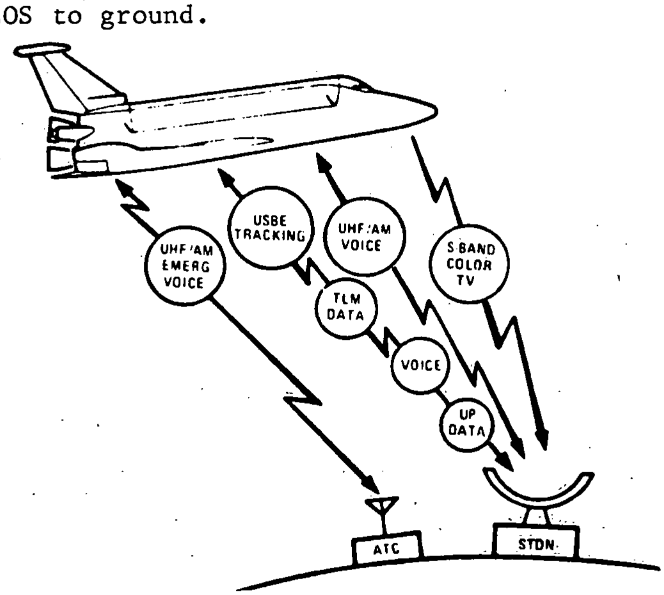


Figure 4-22. EOS External Communication Links

The primary communications link from EOS to ground is via S-band, utilizing an omni directional antenna system. Although there exists the capability to transmit 25 kbps data to ground, this can be augmented by use of the TV mode to effectively increase this capability to 1 Mbps.

Figure 4-23 illustrates the EOS internal communications links together with the interface links.

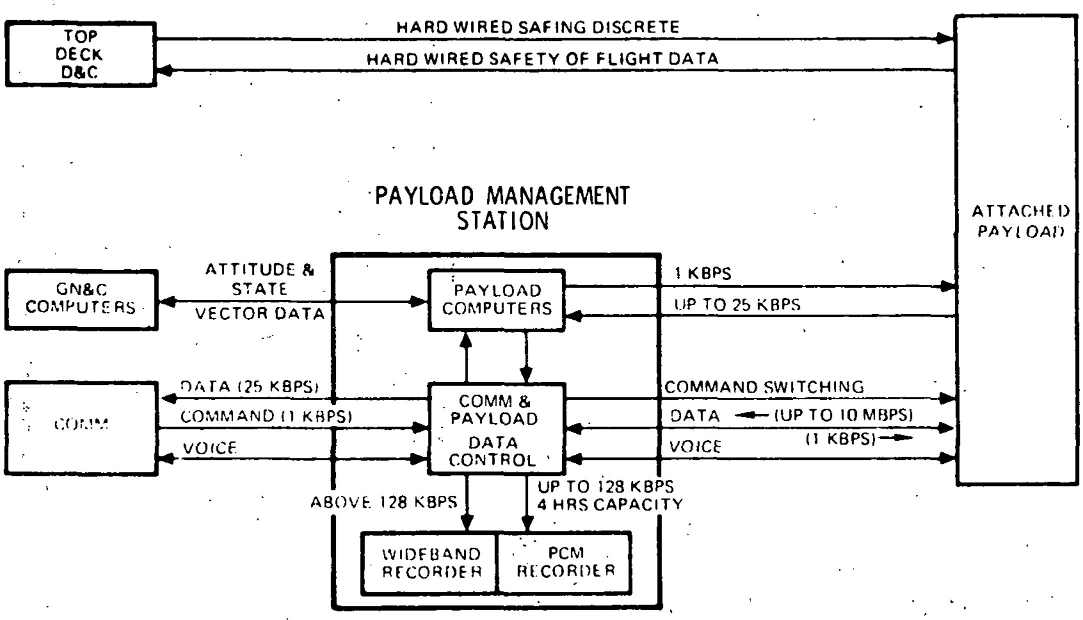


Figure 4-23. EOS Internal Communication Links

It should be noted that although there exists the capability to handle 10 Mbps of data across the interface, the EOS does not have the capability to transmit that to ground.

RAM Design Concept Model

The family of RAM payload carriers includes (1) pressurized, (2) unpressurized, and (3) free-flyers. Figure 4-24 illustrates the three generic concepts.

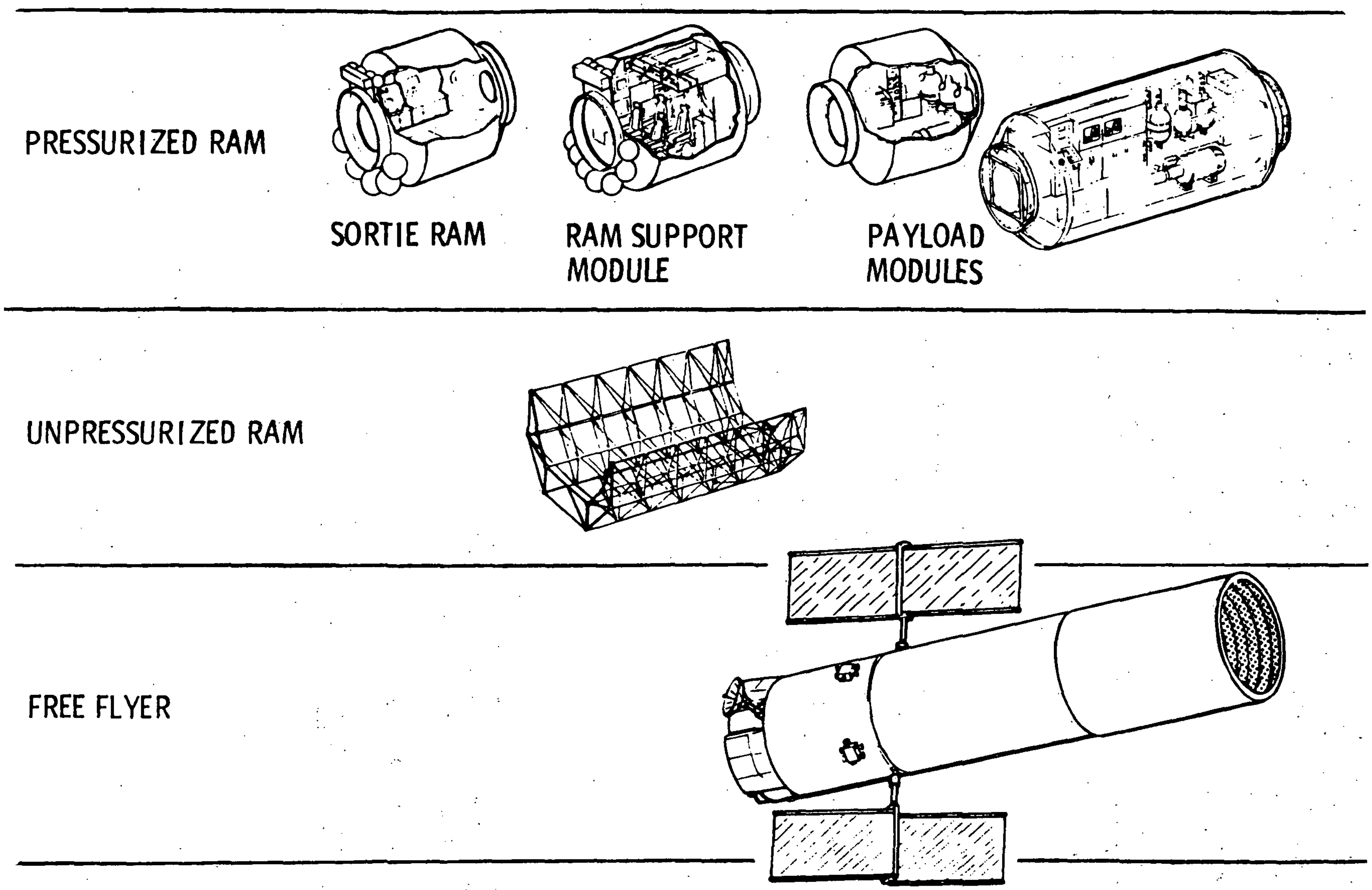


Figure 4-24. RAM Design Concept Models

DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

There are three alternate approaches defined for Attached Element Operations: (1) independent, (2) dependent, and (3) modular dependent (Figure 4-20). In most cases the approaches are not appropriately defined at the element or vehicle level of activity. As a result, one must penetrate to a greather depth, such as the system or subsystem level of activity, in selecting alternate approaches.

Three attached element operational modes were considered in the evaluation: (1) service and checkout, (2) quiescent storage, and (3) RAM operations.

Service and Checkout and Quiescent Storage

By the very nature of their operation, orbital elements involved in service and checkout and quiescent storage are, for all practical purposes, dependent upon the supporting element. In the case of a detached RAM (free flyer) that has returned to the shuttle or the MSS for servicing, it is certainly more appropriate to draw upon the shuttle or the MSS for environmental control support than to provide an independent environmental control system in the RAM. Since detached RAMs are not manned in the free-flying mode, it would not be justifiable to provide environmental control support for such a short period of time during servicing. Like the free flyer being serviced by the MSS, an earth orbit resupply module would depend upon the MSS for environmental control support. Since this module is transported to and from orbit nearly every two months, it would be less than effective to add the additional weight to the resupply module for environmental control, particularly in the light of the fact that the MSS already has that capability.

RAM Operations

Although RAM operations involve the fewest number of element-to-element pairs they represent the most involved functional requirements and operational procedures. In order to proceed with alternate approach selection for RAM operations, an understanding of the objectives and functions of a RAM are requisite.

The allocation of experiments to RAMs, and RAMs to a mission sequence plan represents a major influence on total program cost. Since program cost is a factor that is continually being reviewed and subject to change, it is reasonable to expect that the makeup of RAM payloads is also subject to change. As a result, the alternate approach selections will also be affected. Therefore, in order to pursue the alternate approach selection and preserve a level of flexibility for programmatic changes, much of the analysis was presented parametrically. In addition, wherever possible, the rationale for decision making is documented thus providing a baseline for evaluation of future programmatic changes.

The detail evaluation and rationale are contained in paragraph 4.7 of Volume II, Part 3, Section 4.0. Table 4-12 summarizes the results of the detailed evaluation and selection for a MSS attached RAM.

Table 4-12. Alternate Approach Selection for MSS-Attached RAMs

Function	Approach			Rationale
	Dependent	Independent	Mod. Depend.	
Communications	X			Avail. on MSS
Data management	X			Avail. on MSS
Environmental control	X	X		Certain functions avail. on MSS
Thermal control	X			Avail. on MSS
Attitude control				
>0.25°,0.05°/sec	X			Within MSS capab.
<0.25°,0.05°/sec			X	Augment MSS capab.
Electrical power	X			Avail. on MSS

Throughout the analyses of alternate approach selection for EOS-supported RAM operations there was the intent to utilize as much of the EOS capability as possible without imposing additional requirements on the EOS subsystems. For example, RAMs generating less than 1 Mbps data may utilize the existing EOS capability. RAMs generating data at a greater rate would need to provide the additional hardware to meet the higher requirement rather than impose an addtional requirement on the EOS. The following Table 4-13 briefly summarizes the approach selections for the EOS-supported RAM operations mode, and the rationale for these selections.

Table 4-13. Alternate Approach Selection for EOS-Attached RAMs

Function	Approach			Rationale
	Dependent	Independ.	Mod. Depend.	
Communications				
Tracking and voice	X			Avail. on EOS
data				
<1 Mbps	X			Avail. on EOS
1 to 10 Mbps			X	RAM transmitter and EOS antenna
Up to 50 Mbps		X		Tape storage up to 6 cubic feet plus equipment
Data management		X		Minimize EOS scar and sensitivity to crew size
Eenvironmental Control		X		
Thermal control		X		EOS limited to sustaining itself
Attitude control				
>0.5°, 0.05°/sec	X			Within EOS capab.
<0.5°, 0.05°/sec			X	Augment EOS capab.
Electrical power				
<500 watts ave. & 20 kw-hr	X			Within EOS capab.
>500 watts avg. & 20 kw-hr		X	X	Augment EOS capab.

4.5 ATTACHED ELEMENT TRANSPORT

There are several mission phases involved in the transport of a payload by a propulsive vehicle from one earth orbit to another. Rendezvous, stationkeeping, orbit phasing, and orbit transfer all may be carried out while one element is attached to another. The attached element transport activity includes the support provided by a major propulsive element to an attached payload during and between main engine thrusting maneuvers in earth orbit. Accommodation of the thrust loads at the element pair interface, the control of the propulsive vehicle, and the status monitoring of the payload are part of this activity.

ALTERNATE APPROACHES

Depending upon the operational characteristics of the elements, attachment may be internal or external. Because the EOS orbiter must be able to carry payloads through the earth's atmosphere, its attachment points are located inside the cargo bay. The Tug, on the other hand, often will be moving elements larger than itself and, thus, will employ external attachment. It is assumed that the other propulsive vehicles also will employ external attachment while transporting. The two approaches are illustrated in Figure 4-25.

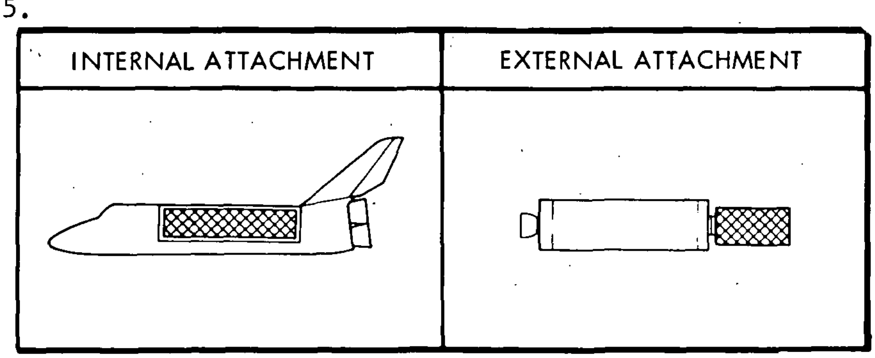


Figure 4-25. Attached Element Transport Alternate Approaches

DESIGN CONCEPT MODELS AND FUNCTIONAL REQUIREMENTS

The obvious major functional requirement is an adequate structural interface to withstand the loads during thrusting maneuvers. The anticipated maximum dynamic loads during EOS maneuver are $N_x = \pm 3.0$ g; $N_y = \pm 0.5$ g; and $N_z = \pm 2.5$ g. These limits are boost and entry load limits.

On orbit maneuver loads are considerably less (<.2 g). Numerous concepts have been proposed for payload retention in the cargo bay. Analyses conducted in conjunction with the payload deployment and retraction interfacing activities indicated that multiple retention concepts - support rings, clamps, and point interconnects - are required. Also, multiple retention or attachment mechanisms are required on single EOS flights because of the difference in up and down payloads. All these concepts can be designed to accommodate the loads of EOS on-orbit maneuvers. The governing criteria are the boost and entry loads. No requirement was identified for EOS orbital transfer thrusting with a payload deployed or berthed external to the cargo bay.

All transport element pairs utilizing any of the four docking concepts evaluated (ring cone, square frame, multi probe and drogue, and international) can accommodate axial thrust loads generated by the Tug, CPS, or RNS. Appendix A8 contains the detail evaluation of these docking concepts as they apply to attached element transport.

Table 4-14 extracted from Appendix A9 summarizes the axial loads that payload/logistic element interfaces may experience. It is assumed that a load distribution transition cone from the docking mechanism to the CPS, RNS, and Tug structure is a basic design of these elements.

Table 4-14. Interface Loads

Configuration	Thrust (Lbs. x 10^{-3})	Axial Load at Interface (Lbs x 10^{-3})
Tug/Tug	70.2	35.1
Tug/RNS		55.9
Tug/MSS		11.8
Tug/RAM		11.8
CPS/OLS (Fully Fueled)	960.0	133.6
CPS/OLS (Nearly Empty)		590.0
RNS/OLS (Fully Fueled)	75.0	22.6
RNS/OLS (Nearly Empty		47.2

DESIGN INFLUENCES AND PREFERRED APPROACH SELECTION

The alternate approach paragraph identifies two categories of approaches; namely, attachment approaches and control approaches. Regarding the attachment approaches, either internal or external, a selection among those two alternatives is not an appropriate consideration. For the elements that are transported by the EOS, attachment points are clearly internal; whereas for all other logistics vehicles (i.e., CPS, RNS, and tug), attachment points are external.

Control Approaches

The operational approaches for controlling one element during transport of another element are related to Rendezvous, Stationkeeping, and Detached Element Operations. Independent, ground control or space control alternatives are evaluated in Section 3.0 of this report. Alternate ground control concepts and potential communication links are also analyzed.

The major factors governing the preferred approach are:

1. Manning status of the elements involved.
2. Relative range between orbital elements.
3. Data transfer requirements.
4. Communication requirements/constraints.
5. Mission characteristics

The elements considered as viable transport vehicles are the EOS, Tug, CPS, and RNS. In the case of the EOS it is always manned and its on orbit stay time is relatively short. Pre-launch planning can be performed in extensive detail by ground equipment. It is recommended that all transport operations involving the EOS be pre-planned by ground control, entered into the EOS computer, and executed by the EOS in an essentially independent mode. Data rates associated with transport operations can readily be accommodated with an S-band omni communications concept. Proper mission planning will alleviate the constraints imposed by the communication gaps with the ground network.

The broad spectrum of potential unmanned Tug operations for transport of other elements is more adaptable to a ground control concept. Kickstage and ground based tug operations will normally result in beyond line of sight operation of the EOS. Similarly space based Tug operations will seldom be conducted in line of sight of one other orbital element. The major exception is the case of a Tug deploying/retrieving a RAM operating in conjunction with the MSS. In these cases, the space controlled approach (MSS controlling the unmanned tug) is preferred.

The independent approach for control of the manned space-based tug is selected (in Part 2 of Volume 2) to provide continuous control and greater accuracy, particularly at closer ranges. Safety is a major consideration in this selection.

External Attachment

Thrust loads experienced during transport of payloads by logistics elements can be grouped into two categories:

1. Loads within the capability of a standard docking concept

2. Loads requiring special adaptations

All transport element pairs except the CPS and its payloads are in the first category. Inasmuch as a standard docking concept, such as the square frame, is adequate, there are no unique requirements or preferred approach selections attributable to the attached element transport interfacing activity. Delivery of payloads on either the RNS or the CPS require additional evaluation.

The transport of the geosynchronous MSS or OLS presents a unique situation. Both the geosynchronous station and the OLS may be assembled and checked out in low earth orbit prior to transfer to their higher energy orbits. The LSB is not configured for orbital assembly and checkout. Two obvious approaches for transport of the station are either in the assembled mode or disassembled/stacked module mode. Analyses conducted in the OLS study indicated that delivery was feasible in the assembled mode by a 75,000-pound thrust RNS. However, bending moments at the junction of the appendages and the core modules can approach two million inch-pounds. Analysis of one contractor mating port concept indicated that an additional 250 pounds of structure would be required at each port on the core modules. Delivery by a non-throttleable CPS (960,000-pound thrust) in an assembled state was impractical. Bending loads at the junction of the core module and its radially mounted modules would approach 12 million inch-pounds. The modules must be transported in a stacked/clustered configuration.

Several concepts were considered that would facilitate assembly on the CLS and would be structurally adequate. The major problem concerned a design that could be carried to orbit in a 15-foot diameter EOS cargo bay. Various "petal" arrangements were examined but none could be contained within a 15-foot diameter. One concept that will fit in the cargo bay, provide adequate structure, and facilitate the assembly process consists of three individual docking adapter "beams" with three docking mechanisms in line on each side of the beam. The outboard docking mechanism on one side of the beam is hinged to facilitate attachment of modules. Upon completion of assembly in orbit, the beams are aligned in 60-degree increments. It is imperative that the modules be stacked as close together as possible for the thrusting maneuver. In line attachment with the desired spacing between modules is not considered feasible with even a manipulator assisting, much less a direct dock concept.

A prime alternate concept to the "beam" approach is similar to the technique for assembly of the modular RNS or CPS. A central core module, approximately 12 feet in diameter, is used as the main interconnect between modules. Multiple pivotal docking ports are mounted on this core module. As each module is mated to the core, it is pivoted in line (major geometric axes) with the core and "latched" to the core. Figure 4-26 illustrates this concept.

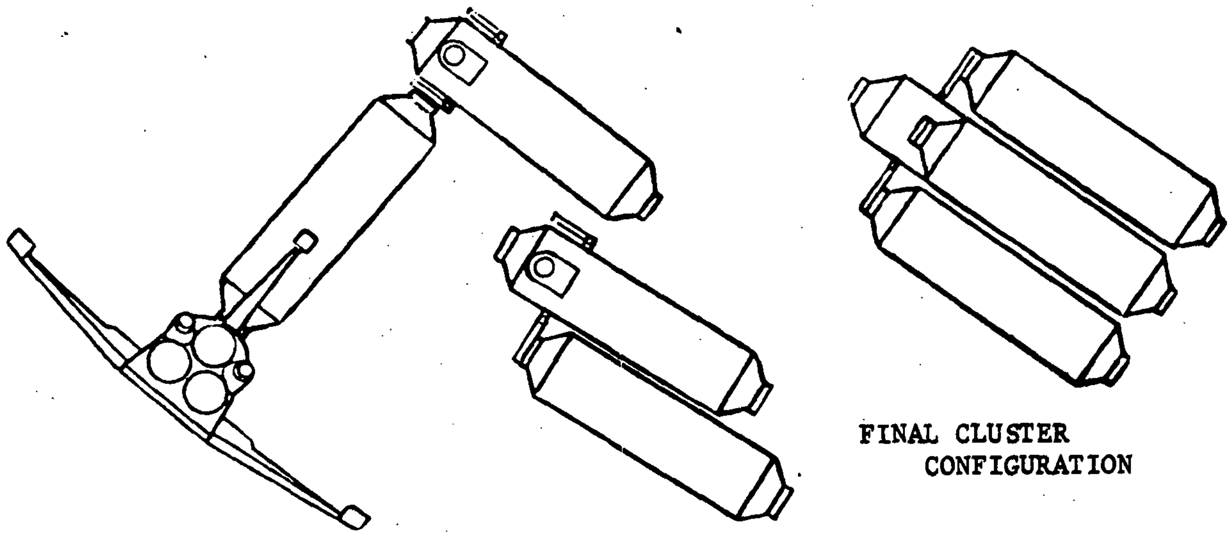


Figure 4-26. Center Core With Multiple Pivotal Docking Ports

Design Influences

EOS internal attachments are not governed by on-orbit transport operations. Launch and return thrust loads will establish the attachment requirements for all EOS payloads.

Tug and RNS thrust loads can be accommodated by any of the four docking concepts evaluated. Further development and eventual standardization of a docking concept must include consideration of the potential thrust loads of these logistics vehicles.

The OLS and geosynchronous stations may require checkout prior to delivery to their operational orbits. If the transport vehicle is the RNS (75K-pound thrust), bending moments up to 2 million inch-pounds could be developed. These potential loads must be considered in designing the structure of surrounding core module docking ports of these stations. Evaluation of one contractor's berthing ports on the MSS indicated an additional 250 pounds of structure was required to each port. Either of the stations could be delivered in an assembled configuration by the RNS with this additional structure. For RNS delivery of either station in a disassembled configuration, a complex assembly/adapter mechanism is required.

The initial delivery of the OLS or geosynchronous station by the CPS requires that the stations be in a disassembled configuration. This requirement is imposed by the high thrust loads produced by the two-fixed thrust engines (960K-lb total). The LSB, of course, must be delivered in a disassembled configuration because it is not designed to be assembled in orbit. The CPS delivery of disassembled modules requires a complex assembly/adapter, capable of withstanding and distributing considerably higher loads than the adapter required for the RNS.